

ISTANBUL TECHNICAL UNIVERSITY ★ GRADUATE SCHOOL

**A QUANTITATIVE APPROACH ON HUMAN FACTOR ANALYSIS IN
MARITIME OPERATIONS**



Ph.D. THESIS

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Department of Maritime Transportation Engineering

Maritime Transportation Engineering Programme

AUGUST 2021

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İSTANBUL TEKNİK ÜNİVERSİTESİ ★ LİSANSÜSTÜ EĞİTİM ENSTİTÜSÜ

**DENİZ OPERASYONLARINDA İNSAN FAKTÖRÜ ANALİZİ ÜZERİNE
KANTİTATİF BİR YAKLAŞIM**

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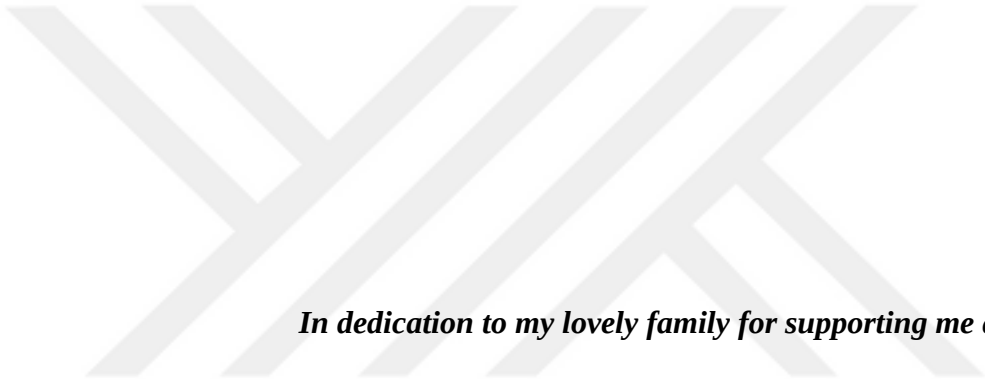
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In dedication to my lovely family for supporting me all the way,



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TABLE OF CONTENTS

	<u>Page</u>
FOREWORD	ix
TABLE OF CONTENTS	xi
ABBREVIATIONS	xiii
SYMBOLS	xv
LIST OF TABLES	xvii
LIST OF FIGURES	xix
SUMMARY	xxi
ÖZET	xxiii
1. INTRODUCTION	1
1.1 Purpose of Thesis	4
1.2 Impact of Thesis	4
2. LITERATURE REVIEW	7
2.1 Literature Review on HRA Methods	7
2.2 Literature Review on HEPs in Maritime Transportation	11
3. METHODOLOGY	23
3.1 Success Likelihood Index Method (SLIM)	23
3.1.1 Overview for SLIM technique	23
3.1.2 Overview for application of SLIM	25
3.2 Type-2 Fuzzy Logic (T2FL)	27
3.2.1 Interval type-2 fuzzy logic (IT2FL)	29
3.2.2 Theory of interval type-2 fuzzy sets	30
3.3 Fault Tree Analysis (FTA)	34
3.3.1 Overview for FTA technique	34
3.3.2 Overview for application of FTA	39
3.4 Proposed Approach: FTA Structure under IT2FS-SLIM	40
4. QUANTITATIVE ASSESSMENT OF HEP	45
4.1 Containerization in Global Maritime Trade	45
4.2 Container Units	46
4.3 Problem Description	51
4.4 Container Handling	55
4.4.1 Operational requirements	55
4.4.2 Hierarchial task analysis	59
4.5 Selection Criteria and Analysis of Marine Experts	61
4.6 Definition of Operation	62
4.7 PSF Derivation	63
4.8 PSF Rating	64
4.9 PSF Weighting	64
4.10 Determination of SLI	67
4.11 HEP Calculation	70

5. HUMAN ERROR CONTRIBUTION TO RISK DETERMINATION	73
5.1 A Quantitative Risk Analysis for Container Loss	73
5.2 Problem Statement.....	73
5.3 Development of a Fault Tree Structure	74
5.4 Analysis of Respondents	76
5.5 Data Derivation	76
5.6 Probabilistic Risk of Container Loss.....	78
5.7 Extended Discussion	80
6. CONCLUSIONS AND RECOMMENDATIONS.....	93
6.1 Conclusive Remarks and Recommendation.....	93
6.2 Contributions to Academic Literature	95
6.3 Contributions to Maritime Transportation Industry	96
6.4 Research Limitations	97
6.5 Further Research.....	98
REFERENCES.....	99
APPENDICES	109
APPENDIX A	111
CURRICULUM VITAE	117

ABBREVIATIONS

ADS-IDAC	: Accident Dynamics Simulator-Information, Decision, Action
APJE	: Absolute Probability Judgment for End Points
ASEP	: Accident Sequence Evaluation Programme
ATHEANA	: Technique for Human Error Analysis
BE	: Basic Event
BIC	: Bureau of International Containers
BN	: Bayesian Network
BWT	: Ballast Water Treatment
CPC	: Common Performance Conditions
CREAM	: Cognitive Reliability and Error Analysis Method
CSC	: The Convention for Safe Containers
CSM	: Cargo Securing Manual
COLREG	: Collision Regulation
DEMATEL	: Decision Making Trial and Evaluation Laboratory
EFC	: Error Forcing Contexts
EmS GUIDE	: Emergency Response Procedures for Ships Carrying Dangerous
EPC	: Error Producing Conditions
ER	: Evidential Reasoning
ERT	: Elicitation Review Team
FEU	: Forty Foot Equivalent Unit
FFTA	: Fuzzy Fault Tree Analysis
FLS	: Fuzzy Logic System
FOU	: Footprint of Uncertainty
FTA	: Fault Tree Analysis
HAZMAT	: Hazardous Material
HC	: High Cube
HCR	: Human Cognition Reliability
HEART	: Human Error Assessment and Reduction Technique
HEI	: Human Error Identification

HEP	: Human Error Probability
HFACS	: Human Factor Analysis and Classification System
HRA	: Human Reliability Assessment
HTA	: Hierarchical Task Analysis
ICBM	: Intercontinental Ballistic Missile
IE	: Intermediate Event
ILO	: International Labour Organization
IMDG	: International Maritime Dangerous Goods
IMO	: International Maritime Organization
ISO	: International Organization for Standardization
IT2FL	: Interval Type-2 Fuzzy Logic System
MARPOL	: International Convention for the Prevention of Pollution from Ships
MCS	: Minimal Cut Sets
MFAG	: Medical First Aid Guide
NARA	: Nuclear Action Reliability Assessment
NPP	: Nuclear Power Plant
OOG	: Out of Gauge
OT/OH	: Open Top / Over High
PIF	: Performance Influencing Factors
PPE	: Personal Protective Equipment
PRA	: Probabilistic Risk Analysis
PSF	: Performance Shaping Factor
QRA	: Quantitative Risk Analysis
SLI	: Success Likelihood Index
SLIM	: Success Likelihood Index Method
SOLAS	: International Convention for the Safety of Life at Sea
SPAR-H	: Standardized Plant Analysis Risk-Human Reliability Analysis
TE	: Top Event
TEU	: Twenty Foot Equivalent Unit
THERP	: Technique for Human Error Rate Prediction
T1FS	: Type-1 Fuzzy Set
UKC	: Under Keel Clearance
USNRC	: US Nuclear Regulatory Commission

SYMBOLS

a, b	: Constant
I_i	: Importance degree of MCS
j	: Occurrence probability of MCS
n	: Number
r_i	: Rating scale of PSFs
Q_0	: Failure Probability of TE
Q_i	: Probability of which one MCS containing the BE
q_i	: Failure Probability of BE
t	: Time
w_i	: Weight of PSFs



LIST OF TABLES

	<u>Page</u>
Table 2.1 : Studies considering the role of HEPs in other high-risk industry.....	13
Table 2.2 : Studies considering the role of HEPs in the maritime industry.....	20
Table 3.1 : Transfer symbols of fault tree.....	35
Table 3.2 : Event symbols of fault tree.....	36
Table 3.3 : Gate symbols of fault tree.....	36
Table 4.1 : Containerized trade data between 2016 and 2019 years.....	46
Table 4.2 : External dimensions of most commonly used ISO containers.....	47
Table 4.3 : Standart ISO container type identification.....	52
Table 4.4 : Hierarchial task analysis.....	60
Table 4.5 : Marine experts' profile details.....	62
Table 4.6 : Determined PSFs for loading operation.....	63
Table 4.7 : Geometric means of PSF ratings based on the experts' evaluations	65
Table 4.8 : Lingusitic terms and their corresponding IT2FSs.....	66
Table 4.9 : Linguistic evaluations of marine experts for each PSF.....	66
Table 4.10 : Calculated average IT2F values.....	67
Table 4.11 : SLI values for "pre-arrival" process.....	67
Table 4.12 : SLI values for "before loading" process.....	68
Table 4.13 : SLI values for "during loading" process.....	68
Table 4.14 : SLI values for "after loading" process.....	69
Table 4.15 : SLI values for "pre-departure" process.....	69
Table 4.16 : Calculated HEP values for "pre-arrival" process.....	70
Table 4.17 : Calculated HEP values for "before loading" process.....	70
Table 4.18 : Calculated HEP values for "during loading" process.....	71
Table 4.19 : Calculated HEP values for "after loading" process.....	71
Table 4.20 : Calculated HEP values for "pre-departure" process.....	71
Table 4.21 : A basic sample of calculation for the HEP.....	72
Table 5.1 : BEs for the loss of container.....	75
Table 5.2 : Geometric means of PSF ratings based on the marine experts' evaluations.....	77
Table 5.3 : Calculated HEP values for each BE.....	78
Table 5.4 : Ranking of BEs according to Fussell-Vesely importance	81



LIST OF FIGURES

	<u>Page</u>
Figure 2.1 : The percentage weight of the utilised methods upon HEP.....	18
Figure 2.2 : Researches upon HEP on maritime transportation by years	18
Figure 3.1 : Membership function of type-1 (Gaussian MF).....	27
Figure 3.2 : Membership function of type-2 (Gaussian MF).....	27
Figure 3.3 : Membership function of type-1 (Trapezoidal MF).	28
Figure 3.4 : Type-2 fuzzy logic system.....	29
Figure 3.5 : Interval type-2 fuzzy logic system	30
Figure 3.6 : The FOU of interval type-2 gaussian MFs	30
Figure 3.7 : Three dimensional visuals of an IT2FS.....	31
Figure 3.8 : The trapezoidal membership function of IT2FS	33
Figure 3.9 : The conceptual framework of the integration	41
Figure 4.1 : An ISO standard 45 ft HC container with markings	48
Figure 4.2 : Visual description of a containership	56
Figure 5.1 : Structure of FT for container loss throughout the cargo operation	79
Figure 5.2 : Comparative representation of weight values for PSFs	83
Figure 5.3 : Comparative representation of HEP values for sub-tasks of "pre-arrival" and "before loading" process	84
Figure 5.4 : Comparative representation of HEP values for sub-tasks of "during loading" process.....	86
Figure 5.5 : Comparative representation of HEP values for sub-tasks of "after loading" and "pre-departure" process	87
Figure A.1 : Port Lisbon cargo operation details	111
Figure A.2 : The designed survey utilised for HEP assessments.....	112
Figure A.3 : The designed survey utilised for risk analysis.....	115



A QUANTITATIVE APPROACH ON HUMAN FACTOR ANALYSIS IN MARITIME OPERATIONS

SUMMARY

The maritime authorities and international organizations have taken the issue of the pivotal role of the human element and its contribution to the safety of ship operations very seriously due to the growing global concern over maritime disasters. At this point, that at least 80 per cent of shipping casualties are related to the human element is underpinned by the conducted studies and investigation reports published by organizations such as IMO (International Maritime Organization), ILO (International Labour Organization) and experts in the field. Despite the economic and technological improvements, since tragic events had caused the worst environmental disasters in recent years, never has the human element been so crucial in the safe operation of ships. However, although the issue of human contribution to unsafe shipboard operations needs to be the focal point of the researches, there has not been a qualified novel study that can meet the gap of the maritime transportation industry.

The purpose of this thesis is to develop a uniquely quantitative approach to evaluate the human error probabilities (HEPs) and to analyse the increasing operational risks due to human errors. In this context, a hybrid approach incorporating Fault Tree Analysis (FTA) and Interval type-2 fuzzy-based Success Likelihood Index Method (SLIM) is developed. The approach, additionally contributing to current human error probability assessment methods in academic literature, is applicable to all shipboard operations regardless of vessel type. With the study under this thesis, it is predicted to provide supportive guidance that enables shipping companies to undertake the early detection of unsafe cargo operations before they get out of control. With the risk assessment concentrated on the concept of the human-related operational failure by implementing the hybrid approach, system vulnerabilities that could result in an undesired event are considerably detected and the awareness in shipping safety management is increased. It is also predicted to reach solid targets by providing both qualitative and quantitative data to maritime container transportation safety as well as an insight into what measures may be necessary to reduce future losses.

A hybrid approach that differs from a traditional HEP assessment, suitable customization to containership platform, a methodology that involves key risk and performance shaping factors (PSFs) based on the literature, industry standards, technical knowledge of marine experts and analysis of marine accident investigation reports, increased consistency in expert judgements, and analysis of the root causes of major risks to operational safety can be mentioned as original aspects of the thesis. Implementation of management of human error probability analysis integrating with risk analysis will provide a consistent tool for the maritime industry. As a result, the study offering proactive solutions to related issues of unsafe shipboard operations that are closely related to both economic and environmental aspects of the maritime transportation industry will provide tangible contributions for enhancing safety.



DENİZ OPERASYONLARINDA İNSAN FAKTÖRÜ ANALİZİ ÜZERİNE KANTİTATİF BİR YAKLAŞIM

ÖZET

Dünya denizcilik otoriteleri ve uluslararası örgütler, son yıllarda yaşanan deniz felaketlerine ilişkin artan küresel endişe nedeniyle, denizcilikte insan unsurunun temel rolü ve emniyetli gemi operasyonlarına katkısı konusunu oldukça ciddiye almaktadır. Dünyadaki ekonomik ve teknolojik gelişmeler ışığında deniz taşımacılığı ve limanlar teknolojik dönüşümlere hızlı yanıt vermiş, operasyonel faaliyetler ve ulaştırmanın etkinliği ve hızlı yükselmiştir. Dünya ticareti, ithal ve ihraç yüklerinin yüzde 75'ini ticari gemiler yoluyla sağlamakta ve bu durum deniz taşımacılığını küresel ticaret hacmi içerisinde yükselen bir trend haline getirmektedir. Ancak, teknolojik gelişmeler ve hacim ile birlikte, son yıllarda yaşanan trajik olaylar, büyük çevre felaketlerine yol açmıştır. İnsan hataları, teknik, mekanik arızalar ve ağır çevresel faktörler deniz kazalarının en yaygın nedenleri olmakla birlikte, Uluslararası Denizcilik Örgütü, Uluslararası Çalışma Örgütü gibi otoriteler ve denizcilik uzmanları tarafından yürütülmüş mevcut çalışmalar ve kaza inceleme raporları, deniz kazalarının en az yüzde 80'inin insan unsurundan kaynaklandığı göstermektedir.

Literatür incelendiğinde, nükleer enerji, petrokimya, havacılık, demiryolu ve lojistik gibi yüksek riskli endüstrilerde, sektör standartları ve gereksinimlerine uygun geliştirilen yöntemler ile insan güvenirliliği ve risk analizleri yapıldığı, ancak denizcilik sektörünün bu konuda açığını kapatabilecek nitelikte spesifik ve tutarlı bir çalışmanın literatürde bulunmadığı görülmüştür.

Bu tezin amacı, insan hatası olasılıklarını ölçen ve insan hatalarından dolayı artan operasyonel riskleri analiz eden benzersiz bir kantitatif yaklaşım geliştirmektir. Buna dayanarak, sektördeki emniyetsiz gemi operasyonlarında insan hatası katkısı hususuna odaklanılmış, geliştirilen yaklaşım gerçek bir konteyner yük operasyonuna adapte edilmiş ve denizcilik alanına tutarlı bir şekilde uygulanması sağlanmıştır.

Konteyner gemisi yük operasyonları, konteyner tipine göre operasyon kısıtlarının ve ek önlemlerin mevcudiyeti, yüksek hız kapasitesi, verimlilik baskıları, yüksek elleçleme ve istifleme miktarları nedeniyle oldukça karmaşık bir operasyon sistemine sahiptir. Bununla birlikte konteyner yük operasyon sistemi, geminin rıhtıma yanaşma öncesinden başlayan ve geminin limandan ayrılışına kadar olan tüm süreçleri kapsar. Bu doğrultuda, yükleme planlanması ve geminin limana gelmesi arasındaki süre "yanaşma öncesi süreç", geminin rıhtıma yanaşması ile operasyonun başlaması arasındaki süre "yükleme öncesi süreç" olarak adlandırılır. Operasyonun başlaması ve operasyonun tamamlanması arasındaki süre ise "operasyon süreci", operasyonun tamamlanması ardından tüm kontrollerin yapıldığı süreç "yükleme sonrası süreç" ve emniyetli seyre başlamak için hazırlıkların tamamlanması ile geminin liman sahasından ayrılması arasında geçen süreç "kalkış öncesi süreç" olarak adlandırılır.

Konteyner gemisi operasyon sistemi, bileşenlerini terminal saha, yük ekipmanı, işgücü ve geminin oluşturduğu koordine bir işleyişe sahiptir. Bu nedenle, yük operasyonları esnasında gemiadamlarından birden fazla görevin eş zamanlı olarak takibi ve gerçekleştirilmesi beklenmektedir. Bu esnada, görev, kişisel veya çalışma ortamı kaynaklı olabilecek, performans şekillendirme faktörü (PSF) olarak adlandırılan her hangi bir faktör, gemiadamının performansı üzerinde olumlu veya olumsuz yönde büyük etkiye sahiptir. Dolayısı ile, insan güvenirlilik analizi veya insan hatası olasılık değerlendirmeleri yapılırken, özellikle konteyner gemisi gibi kritik yük operasyonlarında baskın olan zaman kısıtı, karmaşıklık ve emniyet kültürü gibi etki faktörleri göz önünde bulundurulmalıdır. Bu tez kapsamında deniz operasyonları için özgün hale getirilen performans şekillendirme faktörleri, görev bağlamı insan hatası olasılıkları Başarı Olasılık İndeks Yöntemi ile değerlendirilirken, deniz uzmanları tarafından dilsel olarak ağırlıklandırılmış ve önem derecesine göre ölçekte sıralanmıştır. Uzmanların karar verme süreci, özneliği ve belirsizliği en aza indirmek ve tutarlılığı arttırmak amacıyla aralıklı tip-2 bulanık mantık çerçevesinde ele alınmıştır.

Konteyner gemisi yük operasyonunun her bir alt görevi için elde edilen insan hatası olasılık verileri ve sonuçları değerlendirilmiş ve operasyonel zafiyetleri ve nedenlerini belirlemek üzere bir risk analizi akabinde gerçekleştirilmiştir. Bu kapsamda konteyner gemisi yük operasyonlarında insan hataları kaynaklı yük kaybı riski analiz edilmiştir. Elde edilen sonuçlar çerçevesinde insan hatalarının operasyonel risklere katkıları tespit edilmiş ve yük kaybına neden olan olaylar için önleyici faaliyetler sunulmuştur. Ayrıca elde edilen bulgular, konteyner gemisi kaza raporları inceleme sonuçları ile örtüşmekte olup, tamamen desteklenmektedir.

Literatürdeki mevcut insan hatası olasılık değerlendirme yöntemlerine yüksek katkı sağlayacağı ön görülen hibrit yaklaşım, gemi tipi fark etmeksizin tüm gemi operasyonlarında uygulanabilecek yeterliliktedir. Bu çalışma kapsamında, denizcilik şirketlerine, yük operasyonlarındaki insan hatası kaynaklı zafiyetleri ve riskleri kontrolden çıkmadan erken tespit etmelerini mümkün kılan, destekleyici bir rehberlik sağlanması öngörülmektedir. Geliştirilen hibrit yaklaşım uygulanarak yapılan, insan hatası olasılık değerlendirmeleri ve operasyonel başarısızlık kavramına odaklanan risk değerlendirmeleri doğrultusunda, istenmeyen olaylara sebebiyet veren tüm sistem zafiyetleri önemli ölçüde tespit edilecek ve gemilerin emniyetli yönetimi hususunda farkındalık artırılacaktır. Bununla birlikte, çalışmanın, konteyner taşımacılığı emniyetine kalitatif ve kantitatif veriler sunarak ve gelecekteki olası kayıpları önlemede alınacak gerekli önlemler hususunda fikir sağlayarak amacını gerçekleştireceği öngörülmektedir.

Geleneksel insan hatası olasılık değerlendirmelerinden farklı bir hibrit yaklaşım içermesi, yaklaşımın konteyner gemi platformuna uygun özelleştirilmesi, temel risk ve performans şekillendirme faktörlerini literatür, endüstri standartları, denizcilik uzmanlarının teknik bilgileri ve kaza inceleme raporlarına dayanarak elde eden metodoloji, uzman karar sürecinde arttırılmış tutarlılığın sağlanması ve son olarak büyük risklerin temel neden analizi tezin özgün yönleri olarak belirtilebilir. Bu noktada, insan hatası olasılık değerlendirmeleri ile risk analizini entegre içeren analiz yönetimi, denizcilik sektörü için oldukça tutarlı bir araç sağlayacaktır.

Sonuç olarak, deniz taşımacılığı sektörünün hem ekonomik hem de çevresel yönlerini yakından ilgilendiren emniyetsiz gemi operasyonları hususunda proaktif çözümler sunan bu çalışma, gemilerde emniyetin geliştirilmesine somut katkılar sağlayacaktır.

Yukarıda belirtilen yönleri ile insan hatası olasılık değerlendirmesi araştırmalarına farklı yönlerden yeni bakış açısı getirirken, denizcilik alanında odak bir konuya çözüm üretecektir. Tezin ilk etapta disiplinler arası bir boyutta yürütülmesi ile birlikte denizcilikte insan hatası odaklı çok yönlü bir risk değerlendirme aracının, yazılım ile destekli geliştirilmesi planlanmaktadır. Bu kapsamda, orta ve uzun vadede denizcilik şirketleri, paydaşları ve otoritelerine yeni bir emniyet konsepti olarak sunulacak çalışma, ülkemizi uluslararası düzeyde emniyetli denizyolu taşımacılığı konusunda bilgi ve proaktif çözüm üreten konumuna taşıyacaktır.





1. INTRODUCTION

As the lifeblood of the global economy, maritime transportation is one of the most dangerous industries all over the World. Despite uncertainty remains an overriding issue in the industry, approximately 90 per cent of global trading is carried out by vessels Akyuz and Celik (2018), and international maritime trade continues to expand day by day. UNCTAD (2019) declared the expectations with an annual growth rate of 3,5 per cent over the next five years period. On the other hand, container transportation has become even more important for global maritime trade. According to containerized trade data more than 100 million containers are shipped across the globe on containerships every year and that number has reached approximately 160.5 million containers in 2019 (UNCTAD, 2019). Nevertheless, a considerable amount of tragic events and container shipping disasters where hundreds of containers were lost in a single event have occurred in recent years. The disastrous fires and explosions on Maersk Honam (Wang et al, 2020; Fan et al, 2020), MSC Flaminia (Balisampang et al, 2018; Wróbel et al, 2017), Hyundai Fortune (Balisampang et al, 2018; Ellis, 2011), Sea Elegance (Ellis, 2010, 2011), Zim Haifa (Ellis, 2010; Kelman, 2008; Stuart, 2007), and Hanjin Pennsylvania (Balisampang et al, 2018; Ellis, 2011; Ren, 2009; Cohen, 2006), hull fracture on MSC Napoli (Wróbel et al, 2017; Parunov et al, 2014; Guitart et al, 2008), catastrophic hog on Mol Comfort (Wróbel et al, 2017; Storhaug, 2014), and the broke of Rena in two (Faaij et al, 2017; Schiel et al, 2016), collapsed and fallen overboard containers on MSC Zoe (Jo, 2020; Hwang, 2020) have caused the worst maritime environmental disasters last two decades. As well as the container losses have severe damage to the entire marine environment, some crew members have also died as a result of the accidents, tragically.

Operational activities performed onboard ships involve high-level risk and seafarers are continuously exposed to them every day due to the nature of work. Thereby, identifying the risks factors and minimizing them to an acceptable level is significant to enhance operational safety (Goerlandt, 2015). Human error-related failures, technical, mechanical, and structural failures, and environmental factors are common

causes leading to marine accidents (Karahalios, 2015). The global standard-setting authority for the safety, security and environmental performance of international shipping, the International Maritime Organization (IMO) insistently emphasises the key role of the human element in accidents (IMO, 2003). In the maritime transportation accident-related investigation reports, human error was found to be the major and primary cause of accidents (Corovic and Djurovic, 2013; Harrauld et al, 1998) and at least 80 per cent of shipping casualties are originated from human error (Pazouki et al, 2018; Wiegmann and Shappell, 2017; Akyuz, 2016). Maritime accidents that originate due to natural factors such as heavy weather conditions; unexpected storm, swell-related sea states, unfavourable tides, are noncontrollable and unavoidable and constitutes a limited part of accidents in the maritime history, relatively.

By the reason of the consequences of hazards are potentially catastrophic, risk analysers have been seeking proactive solutions to reduce risks and enhance safety control levels (Akyuz and Celik, 2017). Besides, if a human-related failure does not even lead to catastrophic consequences, it may cause considerable economic losses due to a waste of time in operations. Thus, that human error contribution should be the focal point of the quantitative risk analysis (QRA) in maritime operations is obvious. However, some factors which are any factors relating to the task, individuals or working environment need to contemplate while evaluating the human errors (HEs). These relative factors (Islam et al, 2016) called performance shaping factors (PSFs) are of paramount influence on human performance negatively or positively (Grozdanovic, 2005). To illustrate, Islam et al. (2017) pointed out that workload which is one of the important causes of fatigue, lack of training, and professional experience are the most common PSFs triggering human errors. On the other hand, current methods are evaluated as limited by Konstandinidou et al. (2006) due to not represent all of the important aspects of human performance in terms of understanding the human contribution to risk completely. But, the consequences of human errors can be devastating for the marine environment and port facilities.

It should not be optimistically assumed that technological developments, advanced techniques or well-organised commercial vessel traffic can decrease the rate of accidents, prevent loss of lives or provide safe transport in the seas. Risk analysis being as distinguished from the seafarers' safety performance will lead to insufficient detection in maritime accidents and incidents. In the view of literature research,

although there are some applicable methods presented in terms of the human reliability assessments (HRA), the researches that especially focus on human error contributions in critical shipboard operations are rather limited.

The evaluation of HEPs in the maritime industry is regarded as onerous due to the scarcity of numerical data (Akyuz et al, 2020; Ung, 2019) and the applied HRA methods are not sufficient enough to overcome vagueness and inconsistency (Akyuz and Celik, 2016). Based on this gap, this thesis proposed a hybrid approach through incorporating Fault Tree Analysis (FTA) and Interval type-2 fuzzy-based Success Likelihood Index Method (SLIM) to evaluate the human error probabilities (HEPs), and their contribution to risks and the criticality of the loading operation activities in a container terminal. The main goal of the study is to increase awareness as well as an understanding of all aspects of human errors in undesirable events as an early warning indicator by systematically evaluating how human errors contribute to the operational risks.

SLIM is a substantial and flexible method estimating the human error probabilities (HEPs) (Islam and Yu, 2018; Islam et al, 2016; Park and Lee, 2008; Kirwan 1994; Vestrucci, 1988). In the proposed approach, SLIM is employed by incorporating interval type-2 fuzzy sets (IT2FSs). The IT2FS based SLIM approach has the capability of generating HEPs particularly in cases where the lack of numerical data exists. In the SLIM, the marine experts provide professional judgement to systematically estimates HEP for the designated task whilst IT2FS deals with vagueness and subjectivity in the process of using experts' judgements. As for the last step of the hybrid approach, FTA performs a comprehensive risk analysis and evaluate the criticality of the operational activities.

To achieve this purpose, the following chapters are organised properly throughout the study; the first chapter explains the motivation behind the research and introduction to the importance of human error probability (HEP) analysis in the maritime industry. Additionally, the purpose and impacts of the research and its contribution to the sector are considered, respectively. The next chapter deals with an elaborative literature review upon the approaches of human error probability especially in the maritime industry besides the other risky industries. Because of the significant role of each method in the current study, the third chapter provides a brief literature review and the theoretical background of the methods, respectively and explains their integration in

detail. Chapter four presents an elucidatory example by adopting a real-time containership cargo operation at the port and demonstrates the model on critical activities of loading operation. Chapter five presents the risk analysis evaluating the potential human error contributions to the risk of container loss. The findings and extended discussion are also presented in this chapter. Finally, the conclusion and the contribution of the study to the maritime industry are included in the last chapter.

1.1 Purpose of Thesis

The core purpose of the thesis is to conduct risk analysis for demonstrating the capability of the hybrid approach evaluating the human error contribution to operational failures and accidents. Thus, a new perspective in the marine transportation industry will be introduced. Based on this, the following steps given below are aimed to carry out in accordance with this purpose:

- i) To provide a quantitative hybrid approach yielding a meaningful and useful result.
- ii) To implement the innovative method on real-time shipboard operations.
- iii) To contribute towards the knowledge regarding the potential consequences of human errors.
- iv) To present risk reduction recommendations to minimise the potential for human error during critical ship operations.
- v) To promote and increase safety onboard ships by providing the proactive solutions.
- vi) To provide an insight into losses causation and prevention, including the prospect of using alternative analysis techniques for mitigating operational risks in maritime transportation.
- vii) To contribute to maritime safety management system practices.

1.2 Impact of Thesis

This study is expected to give original contributions to the future studies and the maritime transportation industry by generating a hybrid approach that considers human error contributions in particular to critical shipboard operations. Maritime

safety researchers, maritime safety professionals, ship management companies and relevant maritime stakeholders can integrate the study into their safety management systems to enhance safety level. The outcomes of the thesis are also expected to provide supportive information on risk assessments procedures, particularly for maritime organizations.

Negotiations with the domain experts are ensured for applicability in the maritime field. Thus, academic knowledge is expected to transform into maritime practices. Additionally, the thesis is also supposed to advance the human-based error assessment techniques for maritime transportation in a unique manner since it provides both qualitative and quantitative data in maritime transportation safety. As an output of the thesis, developed hybrid assessment model considering human error probability and human error-related risks also can be useful in other industries where high risk is involved.



2. LITERATURE REVIEW

This chapter provides an elaborative literature review upon HRA methods as well as the approaches for human error probability assessment in the maritime transportation industry together with the other risky sectors.

2.1 Literature Review on HRA Methods

Human behaviours are a source of vulnerability for risky industries that gave birth to the Human Reliability Analysis (HRA) (Di et al, 2015). Thereby, many researchers have focused on the potential human errors to analyse factors that trip humans up to fail and determine the precautions to be taken to minimize the risks. At this point, HRA plays a critical role as a dynamic action for incorporating human factors in risk assessment.

The HRA is a series of techniques for the determination, evaluation and analysis of key tasks and human error in critical operations (Martins and Maturana, 2010). Rashed (2016) defines HRA as a theoretical framework to evaluate human activities for foreseeing the potential human error probability of a given task in a critical operation. There has always been a prevalent debate among the HRA methods about their characteristics, success or failure in the analysis of human errors. Konstandinidou et al. (2006) declared that risk analysis requires a well understanding of the human contribution to risk but some HRA techniques are limited to represent all aspects of human performance. Several current HRA models and methods have been proposed to analyse human errors. Likewise, quantification of that errors is one of the fundamental pursuits in HRA studies (Pan and Wu, 2018). HRA models are generally classified into three categories according to their characteristics; task-related models, time-related models, and context-related models (Spurgin, 2010). Similarly, these methods' developments are classified into three-stage.

First-generation (1970-1990) HRA methods focus on operational human errors and their probabilities. The technique for human error rate prediction (THERP; Swain &

Guttmann, 1983), the human error assessment and reduction technique (HEART; Williams, 1988) and the success likelihood index method (SLIM; Embrey et al, 1984) are the most common first-generation methods for human error likelihood. Also, the accident sequence evaluation programme (ASEP; Swain, 1987), and human cognition reliability (HCR; Hannaman et al, 1984) are the first generation methods having less consideration to human behaviours and generally emphasize the success or failure of activities.

The ignorance of human cognitive activity caused the appearance of the second-generation (1990-2005) HRA methods. A technique for human error analysis (ATHEANA; Cooper et al, 1996), cognitive reliability and error analysis method (CREAM; Hollnagel, 1998), the accident dynamics simulator-information, decision, action in crew context (ADS-IDAC), and standardized plant analysis risk-human reliability analysis (SPAR-H; Gertman et al, 2005) are the second-generation methods focus on human performance factor and the cognitive process by using a cognitive model to explain human error occurrence.

The development of technology in the last century induced third-generation (2005-today) HRA methods that focus on human performance factors relations and their dependencies. The third-generation methods are still in progress. Bayesian network (BN; Almond, 1992) is defined as a third-generation method providing flexibility for representation of the relationship of dependence among the performance shaping factors and defined as graphic frameworks (Calixto et al, 2013).

Regardless of the classification or generation of the HRA methods, the reliability analysis results should be yield an objective quantification and evaluation. From the past to the present, it was realized that human safety behaviours are affected by various internal and external contributing factors, and all generation HRA methods emphasize these relevant factors in context. The name of contributing factors differs among the HRA methods.

So far is known, the term performance shaping factors (PSFs) is widely used in the estimation of human error probabilities to provide qualified and objective consequences. PSFs that are any factors relating to the task, individuals or working environment need to contemplate in evaluating the HEPs are of a paramount influence on human performance negatively or positively (Grozdanovic, 2005). Especially, first-

generation HRA methods concentrate on systematic parameters to modify HEPs with PSFs.

Lack of data is the most crucial source of uncertainty in most HRA methods so adopting expert judgment is inevitable (Xi et al, 2017; He et al, 2008). With substantial domain experience, experts are an integral part of human reliability analysis. Expert judgement technique is utilised to provide HEPs for given tasks or predict the impact of PSFs on the resulting HEPs (Spurgin, 2010). Due to the scarce HEP data in critical operations of risky industries, professional judgement from domain experts has become more essential (Ung, 2018).

THERP method is developed for nuclear power plant operations in order to conduct probabilistic risk analysis (PRA) but it is also appropriate to apply other risky disciplines. It is the application of a judicial procedure to attain HEP estimates in industrial areas. Besides the advantages, the THERP method is limited to error reduction and it does not provide sufficient guidance for modelling the impacts of PSFs (Jae and Park, 1995). Further, PSFs selection is rather limited and crucial organizational factors are mostly ignored. Finally, THERP fails to model human cognitive actions.

HEART is an expert judgement technique. Thereby, it is relatively subjective and relies heavily on the knowledge and experiences of assessors. Error producing conditions (EPCs) represent the factors influencing human behaviours. HEART provides essential error reducing guidance for minimising HEP and further steps are taken to analyze a task compared to the THERP method (Pan and Wu, 2018). However, the derivation of the data is considered questionable by the experts and there are some doubts about the consistency of the method.

Nuclear action reliability assessment (NARA; Kirwan et al, 2004) is a task-related HRA method that covers more tasks as an updated version of the HEART process. NARA has been reviewed by an international group of HRA experts but task descriptions are still not sufficient enough for nuclear power plant (NPP) operations and need to be improved.

ADS-IDAC is a second-generation method that has been developed for the assessment of dynamic reliability in nuclear power plants. The ADS-IDAC considers performance influencing factors (PIFs) to analyze comprehensively. For determining the PIFs, the

method includes organizational factors such as safety culture, communication availability and problem-solving. Compared to traditional risk assessment methods simulation-based model provides a more realistic representation of accident response (Coyne and Mosleh, 2018).

SLIM is a practical and suitable human error probability (HEP) assessment method based on expert judgement. The SLIM approach makes use of expert judgement for choosing proper PSFs and weighting them to determine the importance of that PSFs on human errors and for developing success likelihood index (SLI) in the SLIM process. The SLIM approach has certain limitations in terms of selecting qualified domain experts. Also, it is difficult to ensure that PSFs are completely independent in the process.

SPAR-H method was developed to estimate HEPs used in commercial nuclear power plants. The method comprises of the combination of a simple human reliability representation depend on the cognitive part and an action part with HEPs values and a number of PSFs such as training, complexity, appropriateness of duties etc. Experts assign values for all of the PSFs, regardless of the PSF observability. Based on experts judgement, the method introduces subjectivity into the HEP calculation (Groth and Swiler, 2012).

CREAM is a representative method of the second-generation HRA methods. The factors that affect human performance are known as common performance conditions (CPCs). CREAM focus on cognitive characteristics related to task and context impact rather than task identification. However, CPSs should concentrate on systematic influences rather than individual ones. Then again, organizational factors should be considered more to better determine failures.

The later generation method ATHEANA has been developed by the US Nuclear Regulatory Commission and identifies error forcing contexts (EFCs) exist that influence performance and lead to human errors. ATHEANA utilise the expert judgement elicitation method to generate the HEPs rather than the HEART method. Besides, the method truly reflects the cognitive process of human error occurrence. However, the guidance of the method is rather complicated and subjective due to heavily depending on expert judgements. Also, the quantification method has some weaknesses, so it raises doubts about the consistency of the method.

2.2 Literature Review on HEPs in Maritime Transportation

Human error has been a crucial contributory factor for industrial systems. The consequences of a minor error can cause catastrophic accidents and loss of lives. Therefore human error analysis becomes more prominent in high-risk complex industries, day by day. A variety of HEP applications have been conducted to the different industries such as off-shore (Rozuhan et al, 2020; Islam and Yu, 2018; Deacon et al, 2013; Noroozi et al, 2014; Deacon et al, 2010; Khan et al, 2006; DiMattia et al, 2005) aviation (Kunlun et al, 2011), transportation (Zhou et al, 2019; Wang et al, 2018; Gibson et al, 2012; Kirwan and Gibson, 2008; Park and Lee, 2008; Grozdanovic, 2005), nuclear power plants (Lee et al, 2013; Kirwan et al, 2004, Kirwan, 1997) petrochemical (Castiglia and Giardina, 2013), mining (Wang et al, 2014). Some of the associated studies that considering the role of human error probabilities in the high-risk industries with details are given in Table 2.1.

Human error probability assessments aim to identify and foresee weaknesses in an operation where humans are concerned leading to a failure (Castiglia and Giardina, 2013). The investigation of HEP aims to increase awareness and develop a solution for human errors in unintended accidents and incidents for critical ship operations. Search for an appropriate human error identification (HEI) method that can predict human errors in maritime transportation will always maintain its importance.

Celik and Cebi (2009) proposed an analytical human factor analysis and classification system (HFACS) based on fuzzy analytical hierarchy process (FAHP) with the intent of exploring quantitatively the role of human errors that contribute to the occurrence of shipping accidents. The proposed model is applied to accident case: boiler explosion onboard bulk carrier, The weights of contributing factors are calculated and meaningful information is interpreted to implement preventive actions in the paper. While the paper did not directly introduce HEP assessments, it emphasizes the importance of factors forcing a human to make the error.

Similarly, Chauvin et al. (2013) analysed 27 collisions cases involving 39 vessels using the HFACS tool. The authors focused on the main contributory factors of stated accidents and the existence of patterns of the factors. The analysis results point out that most collisions are due to decision errors. Deficits in inter-ship communications and

bridge resource management deficiencies are directly linked to occurrences of collisions in restricted waters and involving pilot carrying.

The approach based on HEPs assessments was conducted to present a quantitative analysis of the human failure contribution in the case of collusion and grounding of oil tankers operating on the Brazilian coast (Martins and Maturana, 2010). The paper utilized the THERP in the application of the methodology and researched critical points in the ship operations. The authors concluded that the operator should decide where to work to attain a better reduction in the probability of marine accidents such as collision or grounding. The paper does not provide a new methodology to literature but it can be a beneficial reference for the marine industry.

A method that combined absolute probability judgment for endpoints (APJE) and SLIM was utilized to assess HEPs and common human errors in ship collisions (XI and Guo, 2011). Additionally, the AHP method was preferred to weigh the PSFs. Two groups were selected consisting of experts and captains who have practical experiences to judge. Experts judgements were found to be more conservative than captains in the paper. The authors interpret that this result is a benefit for reducing marine HEPs and improving maritime safety. Additionally, results pointed out that the method is feasible for human error researches in maritime transportation.

Akyuz (2015) presented an approach quantifying HEP in the gas inerting operations of crude oil tankers. The author aims to provide a risk-based methodology to assess the risks of human error during critical operations onboard and reduce them accordingly. For this purpose, the paper utilised a quantified CREAM technique to determine the highest HEP values for designated tasks. Accordingly, the paper provides risk reduction measures to mitigate the HEPs. At the end of the study, the paper emphasises the importance of monitoring human performance to minimize catastrophic errors for crude oil tanker safety. The author, later, proposed a fuzzy-based SLIM technique providing more accurate estimation during human error quantification to utilize in the abandon ship procedure in crude oil tanker (Akyuz, 2016). Fuzzy sets overcame the subjectivity in the process of experts' judgments and deal with the vagueness of experts' judgments. In the paper, sending distress message and reporting the situation sub-tasks were found to be the main contributory factors that may cause an error due to having the highest HEP values among the others.

Table 2.1 : Studies considering the role of HEPs in other high-risk industry.

Authors	Population	Methods	Topic	Publisher/Conference
Rozuhan et al. (2020)	Offshore employees	BN	Offshore platform maintenance activities	Applied Ocean Research
Zhou et al. (2019)	Locomotive drivers	HEART	Locomotive driving process	Reliability Engineering and System Safety
Islam and Yu (2018)	Offshore employees	SLIM/HEART	Offshore platform maintenance activities	Methods in Chemical Process Safety
Wang et al. (2018)	Locomotive drivers	HEART-RARA	High-speed railway dispatching	International Journal of Industrial Ergonomics
Wang et al. (2014)	Coal miners	SLIM	Coal mine evacuation	Journal of Loss Prevention in the Process Industries
Noroozi et al. (2014)	Offshore employees	HEART	Maintenance operations	Process Safety and Environmental Protection
Lee et al. (2013)	NPP operators	K-HRA	Soft control operations	Annals of Nuclear Energy
Calixto et al. (2013)	Oil&gas installation employees	SLIM/SPAR-H/BN	Turbine maintenance tasks	Open Journal of Safety Science and Technology
Tu and Lou (2013)	Crane operators	SLIM	Lifting operations	International Conference on Mechatronic Sciences,Electric Engineering and Computer

Table 2.1 (continued) : Studies considering the role of HEPs in other high-risk industry.

Authors	Population	Methods	Topic	Publisher/Conference
Deacon et al. (2013)	Offshore employees	HEART-HAZOP	Offshore evacuation systems	Safety Science
Castiglia and Giardina (2013)	Operators	Fuzzy-HEART and CREAM	Maintenance operations in refuelling station	International Journal of Hydrogen Energy
Kunlun et al. (2011)	Aircrew	HEART	Flight under icing condition	Journal of Procedia Engineering
Deacon et al. (2010)	Offshore employees	HAZOP/ARAMIS	Offshore emergency musters	Safety Science
Park and Lee (2008)	Drivers	AHP–SLIM	Driver’s error	Reliability Engineering and System Safety
Khan et al. (2006)	Offshore employees	HEPI-SLIM	Mustering operation	Safety Science
Grozdanovic (2005)	Operators	APJ-SLIM	Electro-power systems/railway	International Journal of Occupational Safety and Ergonomics
DiMattia et al. (2005)	Offshore employees	SLIM	Offshore platform musters	Journal of Loss Prevention in the Process Industries

In the same year, Rashed (2016) illustrates the basic and extended version of CREAM for critical shipboard operations safety. The author concluded that the CREAM tool depending on the cognitive behaviours of humans is beneficial and suitable to be applied to shipboard operations.

Akyuz and Celik (2017) proposed a quantitative approach considering the role of the human factor in maritime environment risk assessment. SLIM extended with Fuzzy logic is utilized to calculate the occurrence of HEPs. The proposed approach is applied to a specific case shipboard: Ballast Water Treatment (BWT) system. The authors also aim to enhance the safety control level and reducing the potential impacts of human errors on marine ecology. Maintenance activities are found as the riskiest phase of the Ballast Water Treatment process, therefore risk control measures are recommended to mitigate risks having the highest HEP values. In the previous research, the authors investigated the HEPs during Cargo loading operation (loading process of propylene oxide) in oil/chemical tanker ship by proposing a hybrid approach that combines the AHP technique into the HEART method (Akyuz and Celik, 2016).

XI et al. (2017) proposed a modified CREAM methodology based on an evidential reasoning (ER) approach and a decision making trial and evaluation laboratory (DEMATEL) technique to make HEP quantification in CREAM rational. The authors presented an illustrative case study investigating the collision avoidance of a particular scenario in Shanghai coastal waters to demonstrate the use of the proposed methodology. The obtained results pointed out that the new method has shown its superiority due to deal with the uncertainties caused by insufficient information and data in the evaluation of CPCs compared to the previous studies. In addition, the technique based on the DEMATEL has allowed for different importance of CPCs and more sensitive estimation of HEP.

The HEP assessments method, SLIM, was proposed to determine the HEPs values for the maintenance procedures of the marine engines (Islam et al, 2016, 2017b). The authors aim to minimize the marine accidents related to human error and preclude them from the maritime industry. The rating and weighting of the six PSFs are assigned by experts for the maintenance activities of the marine engines and training and experience are determined as the most important among the six. Among the 43 activities, checking of fuel and lubricating oil filters pressure difference and renew

filters activity were found to be the highest HEP values. This means that it has a high probability of accidents occurrences. Accordingly, in the latter studies, the authors proposed HEP assessment methods HEART and BN for Marine Engine activities such as Exhausted Turbocharger and Fuel Pump Maintenance (Islam et al, 2018; Islam et al, 2017a).

Wu et al. (2017) investigated the developments of the maritime accident and proposed an evidential reasoning-based CREAM approach to estimate the HEPs in the maritime accident process. The proposed approach is applied to the human reliability analysis of a ship capsizing accident. The authors evaluate that the proposed CREAM predict the HEP with good accuracy but uncertainty still exist and need to be reduced.

Ernstsen and Nazir (2018) conducted a study on human error in pilotage operations and utilized a systematic human error reduction and prediction approach (SHERPA) to analyse the most frequent human errors (HEs). In the paper, communication and action omission errors were found to be the most prone to human errors in the pilotage operations.

Zhou et al. (2018) proposed a quantitative human reliability analysis model based on a fuzzy and BN-CREAM evaluating human errors for the tanker operational safety. The obtained results of the case study conducted in the tanker shipping industry pointed that the HEP assessment considering the proposed HRA model is able to provide reliable human performance failure results as well as the model is consistent with the original CREAM approach. Further, that most of the 18 crew members are relatively reliable, with the control mode of tactical, which also fulfils the real situations is concluded.

Likewise, in the previous year, Zhou et al. (2017) applied CREAM as well as the Markov method analysing the human reliability and mean time to human error for identifying the contributory factors to the accidents/incidents in tanker shipping. In the paper, as different from the original CREAM that just gives the control mode and the probability interval of an action failure, obtained quantitative results were found to be satisfactory.

Since human error plays an important role in triggering ship accidents, Ung (2018) performed a risk study evaluating the contribution of human error to oil tanker grounding. The author proposed a logical safety structure of oil tanker grounding based

on fault tree analysis (FTA) under which a novel fuzzy-CREAM model is constructed. In the parameter synthesis process, beneficial information was deliberated from each rule and all reasonable outcomes were also obtained by Bayesian Reasoning. In the study, fatigue and Collision Regulation (COLREG) violations were found to be the crucial elements in triggering the occurrence of ship powered groundings according to the sensitivity analysis. Furthermore, route drawing failure, anchorage selection failure, incorrect under keel clearance (UKC) and squat and detection error were the important basic events demanding more attention compared to others.

In his next study, Ung (2019) investigated the risk of human error contribution to an oil tanker collision. To conduct a human error assessment, the collision probability of the oil tanker was evaluated using the FTA structure under which a modified fuzzy BN-based CREAM. In this study, it is concluded that lack of communication between ships, lack of bridge resource management communication, COLREG violations and fatigue were found to be the important elements having great potential for contributing to oil tanker collision with higher occurrence rates. Besides, the number of simultaneous goals in the bridge was the common performance condition that considerably causes the occurrence of all the human error basic events.

An expert judgement technique, SLIM was employed by incorporating interval type-2 fuzzy sets (IT2FSs) to assess the potential contribution of human errors and to determine the operational vulnerabilities throughout the loading operation onboard containership due to its considerable risks for the marine environment (Erdem and Akyuz, 2021). The obtained results pointed out that the success likelihood and safety performance of the ship crew declines drastically towards the end of the operation process with the effects of PSFs. Especially, safety culture, experience, fatigue, and time limitation were found to be highly effective on crew performance. Further, that the IT2FS-SLIM approach can effectively be applied for determining the vulnerabilities and critical human errors in the operational process were corroborated in the study.

To comprehensively contextualise, Figure 2.1 provides a graph for the percentage weight of the utilised methods in which the studies focused on human error probability in maritime transportation for the last decade. At this point, CREAM (38 %) has come to the fore as the most preferred method for human error probability assessment in the maritime industry.

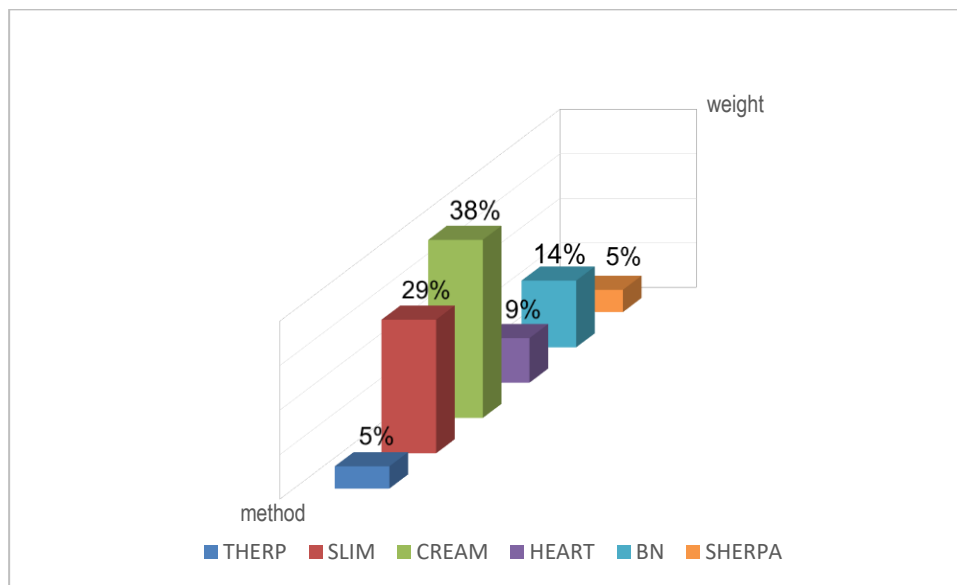


Figure 2.1 : The percentage weight of the utilised methods upon HEP.

There have been totally 19 researches existing in literature in respect of quantitative HEP method application in maritime transportation industry between 2010-2021. Accordingly, Figure 2.2 provides the graphical distribution of these researches by years.

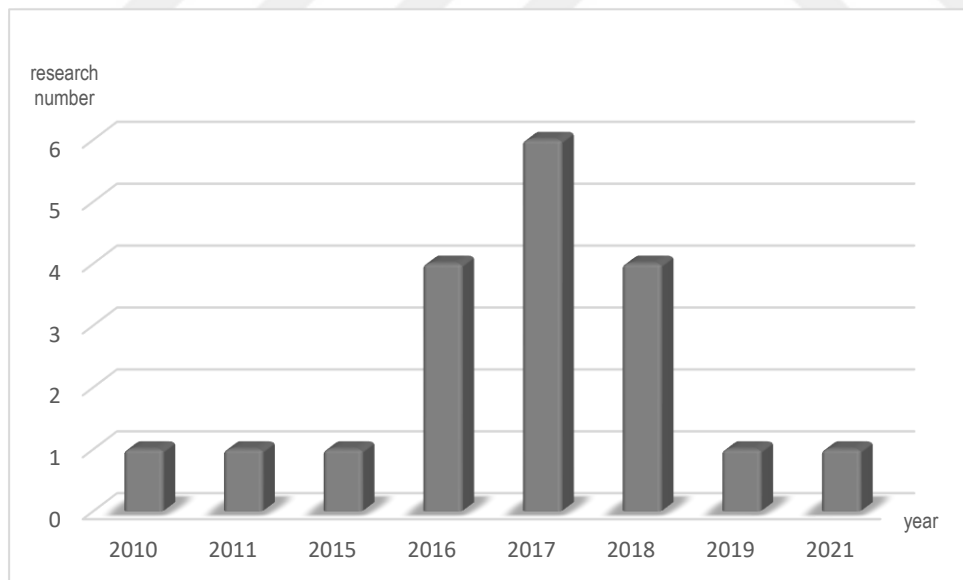


Figure 2.2 : Researches upon HEP on maritime transportation by years.

The graphical representation points that the studies focused on human error probability have been increasing since 2010. The topic has become more prominent in recent years since human errors are the major contributory factor of maritime accidents. The above-

mentioned studies are also proven evidence for the significance of quantifying human error probabilities in maritime operations.

The summary of literature research conducted between the 2010-2021 years for HEP assessments in maritime transportation is given in Table 2.2. The following significant points can be concluded from the literature review:

- The studies considering HEP assessments are scarce in the marine transportation industry.
- Most of the HEP assessments techniques are subjective due to heavily depending on expert judgements so needs to be improved.
- The current HEP assessments methods have some weaknesses so raise doubts about the consistency.
- The derivation of the data is commonly considered as questionable in high-risk industries as the maritime industry.
- A specific quantitative hybrid approach needs to be developed for the maritime transportation industry.

Within this context, the goal of the thesis is to fill the gap in the literature and develop a quantitative hybrid approach for the assessment of HEPs in critical ship operations.

Table 2.2 : Studies considering the role of HEPs in the maritime industry.

Authors	Population	Methods	Topic	Publisher/Conference
Erdem and Akyuz (2021)	Ship crew	IT2F-SLIM	Containership operations	Ocean Engineering
Ung (2019)	Ship crew	FTA-Fuzzy BN-CREAM	Collusion	Ocean Engineering
Ung (2018)	Ship crew	FTA-Fuzzy CREAM	Grounding	Safety Science
Ernstsen and Nazir (2018)	Pilots/Captains	SHERPA	Pilotage operations	Marine Navigation and Safety of Sea Transportation
Islam et al. (2018)	Ship crew	BN	Maintenance operations	Safety and Health at Work
Zhou et al. (2018)	Ship crew	Fuzzy BN-CREAM	Tanker operations	Safety Science
Zhou et al. (2017)	Ship crew	Markov-CREAM	Tanker operations	Safety Science
XI et al. (2017)	Ship crew	CREAM	Collusion	Ocean Engineering
Wu et al. (2017)	Ship crew	CREAM	Ship capsizing accident	Risk Analysis
Islam et al. (2017a)	Marine engineers	HEART	Marine engine maintenance	Loss Prevention in the Process Industries
Islam et al. (2017b)	Marine engineers	SLIM	Maintenance activities	Safety Science

Table 2.2 (continued) : Studies considering the role of HEPs in the maritime industry.

Authors	Population	Methods	Topic	Publisher/Conference
Akyuz and Celik (2017)	Ship crew	Fuzzy- SLIM	BWT operations	Human and Ecological Risk Assessment
Rashed (2016)	Ship crew	CREAM	Shipboard operations	Journal of Shipping and Ocean Engineering
Islam et al. (2016)	Marine engineers	SLIM	Maintenance activities	Journal of Ship Production and Design
Akyuz and Celik (2016)	Ship crew	AHP-HEART	Cargo loading operation	Loss Prevention in the Process Industries
Akyuz (2016)	Ship crew	Fuzzy- SLIM	Ship evacuation	Ocean Engineering
Akyuz (2015)	Ship crew	CREAM	Gas inerting operation	Safety Science
XI and Guo (2011)	Ship crew	APJE-SLIM	Collusion	Applied Mechanics and Materials
Martins and Marturana (2010)	Ship crew	THERP/FTA/ETA	Collision and grounding	Risk Analysis



3. METHODOLOGY

This chapter introduces a hybrid approach incorporating Fault Tree Analysis with Interval type-2 fuzzy logic (IT2FL) based SLIM to evaluate the HEP, human error contribution to risks and the criticality of the loading operation activities. The main goal of the approach is to systematically evaluate the human error probabilities as well as their contribution to risks associated with the most crucial vulnerabilities in the operational process at the port. Based on this, the SLIM technique quantifies the human error probabilities based on expert judgement. Interval type-2 fuzzy sets are utilized to deal with vagueness and subjectivity in the process of using experts' judgements. As the last step, a comprehensive risk analysis is performed to identify the human-related vulnerabilities in the operational process to enhance safety.

Because of the significant role of each method in the approach, a literature review and the theoretical background of them are provided, respectively. The conceptual framework and the system design of the quantitative approach, the pros and cons items touch on strengths and weaknesses of the methods are also introduced in the chapter.

3.1 Success Likelihood Index Method (SLIM)

3.1.1 Overview for SLIM technique

The SLIM is the first-generation, task-related HRA technique developed to quantify human error with a decision-analytic approach. The technique is a simple and flexible approach (Islam et al, 2016; Bell and Holroyd, 2009; Kirwan 1994; Vestrucci, 1988) that makes use of domain expert judgment to select and weigh the PSFs according to their perceived contribution in a given task for HEP prediction (Spurgin, 2010). It mainly contextualises the likelihood of a human error occurring in specific tasks with the effect of some relative factors (Islam et al, 2016) and provides a practical tool utilising anchor values to identify the scale of likely HEPs. The factors called PSFs, affect human performance in the task context, so increasing or decreasing the human error probability (Pan and Wu, 2018). The analysing and assessment of human error on the basis of PSFs are crucial to prevent accidents and incidents in a high-risk

industry. To illustrate, extreme weather conditions, ship motion, noise and workload are the most important factors that affect seafarers' performance negatively, hence, increasing the chance of error and quite likely can cause injuries or loss of life (Islam et al, 2017b). Therefore, in the SLIM process, the influence rate of PSFs on human activities is the core point in the development of the SLI for each determined task and HEP is derivated with this index. At this point, it is rather important to define systematic PSFs rather than all PSFs. Domain expert judgements that rely on the experiences and knowledge are used to select a set of PSFs and to weigh their perceived importance on a given task. Inconsistent results can be found unless the expert elicitation process is carried out exactly. Since, the SLIM heavily bases on domain experts' judgements to predict human error due to the scarce of data (Park and Lee, 2008), selecting appropriate domain experts is another sore point of the method. Nevertheless, it is practical and rather quick in the prediction of the HEP process that requires lengthy decision making in case of hard to acquire error data (Akyuz, 2016). To obtain HEP values, the quantification process can be divided into five main parts in the SLIM approach as follows:

- i) PSF derivation
- ii) PSF rating
- iii) PSF weighting
- iv) SLI determination
- v) HEP calculation

The determined scenario activities are considered as different tasks under the influence of different PSFs. PSFs are rated independently ($r_i, 0 \leq r_i \leq 1$) through experts judgements by assuming that 0 for the worst and 1 for the best conditions relevant to each performance shaping factor on each activity. Accordingly, PSFs are weighted (w_i) through experts judgement by assigning the maximum value repeatedly to the most significant one. Once the ratings and weights have been nominated, PSFs are quantified in SLIM and converted into the preference index. All the tasks are placed under a success likelihood scale. The SLI values are calculated by equation (3.1) given below:

$$SLI = \sum_{i=1}^n r_i w_i, \quad 0 \leq SLI \leq 1 \quad (3.1)$$

In equation 3.1, SLI expresses the success likelihood index, n expresses the number of PSFs, r_i represents the rating scale of PSFs and w_i represents the weight of the PSFs' relative importance.

The final significant step of the SLIM approach is HEP calculation. The conversion of the SLI values to HEP is achieved by using the linear logarithmic function, logarithm with base 10 represented as log base 10 (Chien et al, 1988). Equation (3.2) used for SLI conversion is given below:

$$\text{Log} (HEP) = aSLI + b \quad (3.2)$$

In equation 3.2, HEP expresses the human error probability and a and b are constants acquired from the HEPs for the sub-tasks with the highest and lowest SLIs.

In the current study, the SLIM approach is utilized for the assessment of the human error probability throughout the critical containership loading operations.

3.1.2 Overview for application of SLIM

The SLIM approach was first developed by Embrey and his associates (Embrey et al, 1984; Embrey et al, 1994) to predict occurrence likelihood of human errors (HEs) under the influence of combined factors in a Nuclear Power plants with the support of the US Nuclear Regulatory Commission (USNRC) (Wang et al, 2014; Calixto et al, 2013). Afterwards, SLIM has also been successfully applied in other high-risk industries such as offshore (Islam and Yu, 2018; Abbasi et al, 2015; Noroozi et al, 2013; Khan et al, 2006; DiMattia et al, 2005; DiMattia, 2004; Bea, 2001), chemical (Embrey et al, 1994), process (Wang et al, 2014), logistic (Park and Lee, 2008), railway (Grozdanovic, 2005), and maritime (Akyuz and Celik, 2017; Islam et al, 2017; Islam et al, 2016; Akyuz, 2016; XI and Guo, 2011).

Marine operations pose a non-negligible hazard for human life and the environment due to the nature of work. However, it can be concluded from the literature review that the use of the SLIM technique that quantifies human error and provides accurate prediction is rather limited in the maritime transportation industry. Nonetheless, there have been some significant studies conducted with the SLIM technique. To illustrate, Akyuz (2016) utilised a fuzzy logic-based SLIM technique to assess the human error

probability that occurred while achieving a certain task during the abandon ship procedure. The hybrid approach was found to be beneficial in terms of providing more accurate human error estimation during quantification and SLIM has provided a quick tool in the evaluation of HEP. Likewise, Akyuz and Celik (2017) proposed a hybrid approach to calculate HEP and applied this quantitative approach to a specific case on board ship: Ballast Water Treatment (BWT) system. In order to improve consistency and reduce the subjectivity of experts' judgements, SLIM has been extended with fuzzy logic in the study. Whilst this extended approach was developed for human error probability assessment, it highlights the importance of the human factor in maritime risk assessments.

Islam et al. (2016) used the technique intending to determine the HEPs for maintenance procedures of marine engines. SLIM was preferred due to the unavailability of human error data for marine operations. Whilst this study mainly handled human error probability assessment in maintenance procedures, it also aims to minimize human error by highlighting the importance of human factor and preventing human-based accidents in the shipping industry. A similar study was conducted by Islam et al. (2017b) to develop a monograph for assessing the human error probability in marine operations. Due to the scarce of data, the SLIM has been successfully applied to estimate HEP in the maintenance operations of the ship. The developed monograph has been evaluated as favourable and helpful for masters and chief engineers in the decision making process for various maintenance activities.

XI and Guo (2011) utilised a combined approach to assess HEPs in ship collisions due to the lack of data in the maritime industry. An analytical hierarchy process has been used to acquire each PSF weight. Further, APJE and SLIM techniques have been combined for the estimation of human error probability. The method was found as favourable for human error researches in maritime transportation.

Another innovative technique, the so-called BN-SLIM, was utilised by Abrishami et al. (2020) for improving the performance of SLIM. With this technique developed by mapping SLIM in BN, it is aimed to model causal links between performance shaping factors and human errors as well as the dependencies among human errors. The paper concluded that BN-SLIM provides a better estimation of human error probability by considering conditional dependencies resulting from common PSFs.

3.2 Type-2 Fuzzy Logic (T2FL)

The type-2 fuzzy set was originally introduced by Zadeh (1975) as an extension of the concept of the type-1 fuzzy set (T1FS). Type-2 fuzzy logic (T2FL) is a generalization of conventional fuzzy logic in terms of uncertainty that is not only limited to the linguistic variables but also is exist in the definition of the membership functions (Castillo and Melin, 2008). T2FSs are used in circumstances that it is hard to determine an accurate membership function for a fuzzy set. Namely, they are more efficient in determining the membership grade is fuzzy even as a crisp number in $[0,1]$.

The differences between the membership function of Gaussian Type-1, as in Figure 3.1, and membership function of Gaussian Type-2, as in Figure 3.2, and Trapezoidal type-1 membership function as in Figure 3.3, are visually expressed below.

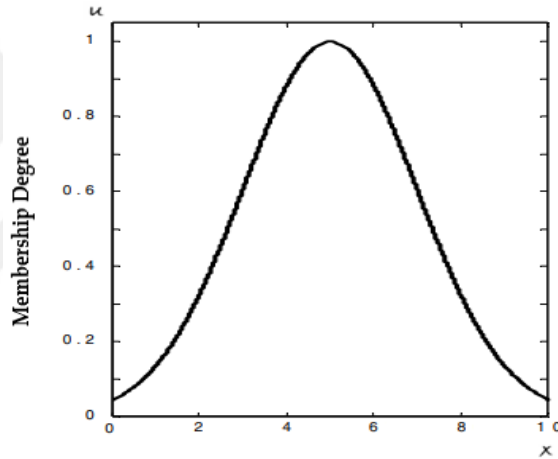


Figure 3.1 : Membership function of type-1 (Gaussian MF).

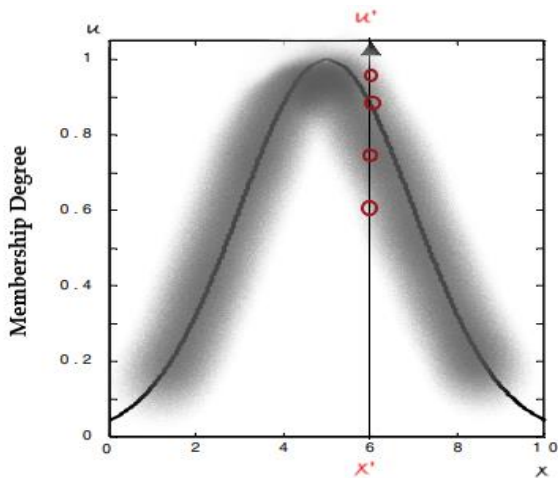


Figure 3.2 : Membership function of type-2 (Gaussian MF).

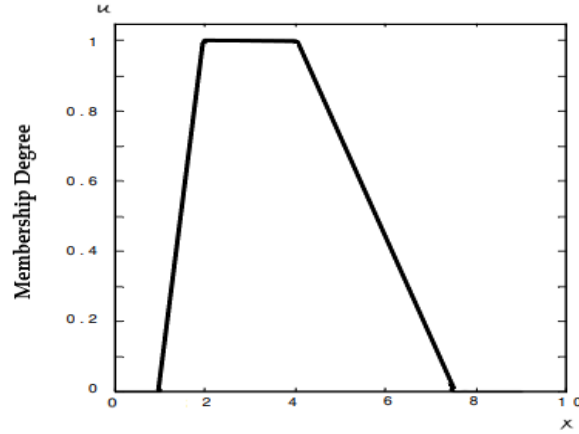


Figure 3.3 : Membership function of type-1 (Trapezoidal MF).

The type-2 membership function is obtained by blurring the Type-1 membership function. This three-dimensional membership function (μ') taking on varied values, characterizes T2FS for all $x \in X$. In that case, a T2FS has three-dimension, and the third dimension specifies the degree of membership of the two-dimensional membership function at each point in its two-dimensional area (Solo, 2015). T2FS, therefore, handle uncertainties much better due to providing more various parameters by comparison with T1FS (Erdem and Akyuz, 2021).

A type-1 fuzzy logic system (T1FLS) consists of a knowledge base, fuzzification interface, inference system, de-fuzzification interface (Mendel, 2001). However, the basic principles of both FLSs are similar and do not change from type-1 to type-2 since they are independent of the nature of membership functions. The difference between type-2 and type-1 is just related to the nature of the membership functions. Whereas the membership function of T1FS is totally crisp, the membership functions of T2FS are fuzzy. Accordingly, in the higher-type case, the higher degree of fuzziness is expressed. The systematic design of T2FLS is depicted in Figure 3.4. Output process including type-reducer and defuzzifier mechanism is the main difference between type-1 and type-2 fuzzy logic systems. While the defuzzifier mechanism traduces one output to crisp value, the type reducer mechanism converts T2FSs into T1FSs. Based on this process, a type-1 fuzzy set output is generated (Mendel, 2007).

The fuzzifier is the other mechanism of the basic structure, and it translates the crisp values to fuzzy values. As for the inference mechanism, it combines the rules and provides a mapping from input T2FSs to output T2FSs (Castillo et al, 2008).

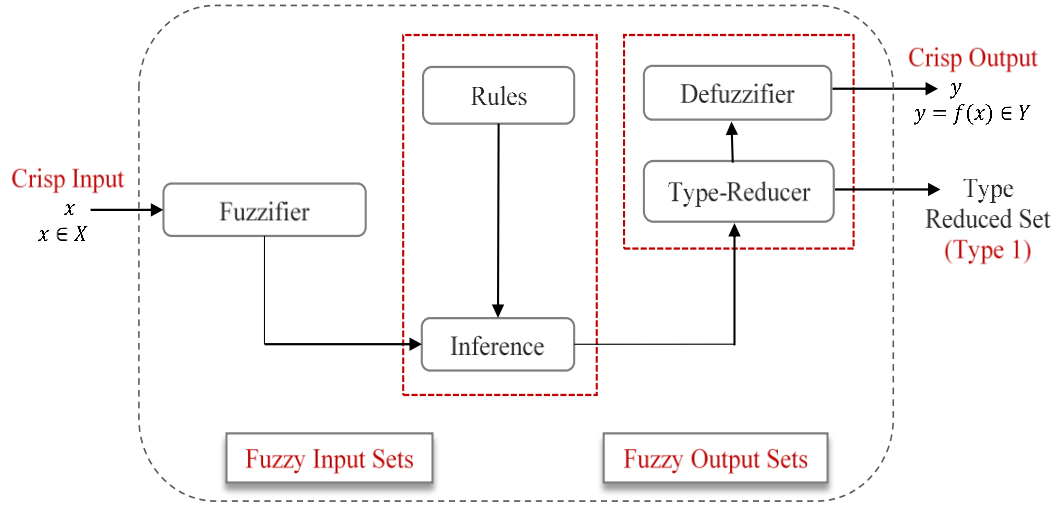


Figure 3.4 : Type-2 fuzzy logic system.

The knowledge of humans is stated as a set of fuzzy rules in a fuzzy logic system. A T2FLS is characterized by IF (antecedent)-THEN (consequent) rules and expresses a fuzzy relationship and a suggestion (Mendel et al, 2006). The structure of rules in a T2FS has no difference compared to T1FS, however, in the T2FS, the antecedents and consequents are expressed by T2FSs.

3.2.1 Interval type-2 fuzzy logic (IT2FL)

Interval type-2 fuzzy set can be considered to be a special case of a generalised T2FS. Although generalised T2FSs are successfully used, IT2 FSs are favoured commonly due to their reduced computational effort and convenience (Akyuz and Celik, 2016). Generalised T2FSs are of complex computational steps (Mendel et al, 2006) as well they are appropriate to be used in a wide range of problems (Melin and Castillo, 2004). However, they have not commonly been utilized in real case applications (Kahraman et al, 2014). Mendel (2007) suggested IT2FSs as a model for words, since the words have different meanings to different people and to overcome this uncertainty, a fuzzy set model is needed for words.

In traditional HEP approaches, the insufficient data mostly collected from linguistic expressions are subjective and uncertain and also have limitations to present the safety performance of humans completely. However, in IT2FSs, linguistic variables are useful in dealing with complex conditions and make more sense than facts and figures by reflecting uncertainties better. The concept of linguistic variables was firstly introduced by Zadeh (1971) as an effective alternative approach to modelling human

thinking. The Interval type-2 fuzzy logic system (IT2FLS) depicted in Figure 3.5 differ in terms of rules & inference interaction compared to the system of a general T2FL.

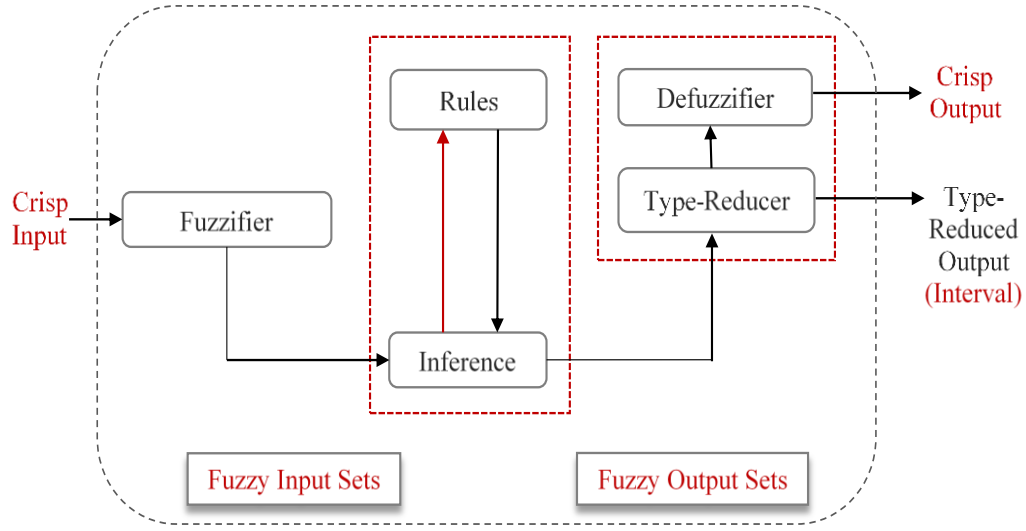


Figure 3.5 : Interval type-2 fuzzy logic system.

3.2.2 Theory of interval type-2 fuzzy sets

A T2FS is characterized with a superior (upper) membership function and an inferior (lower) membership function and the interval between these functions denotes the bounded region called the footprint of uncertainty (FOU).

Figure 3.6 denotes both upper and lower Interval type-2 membership functions and footprint of uncertainty.

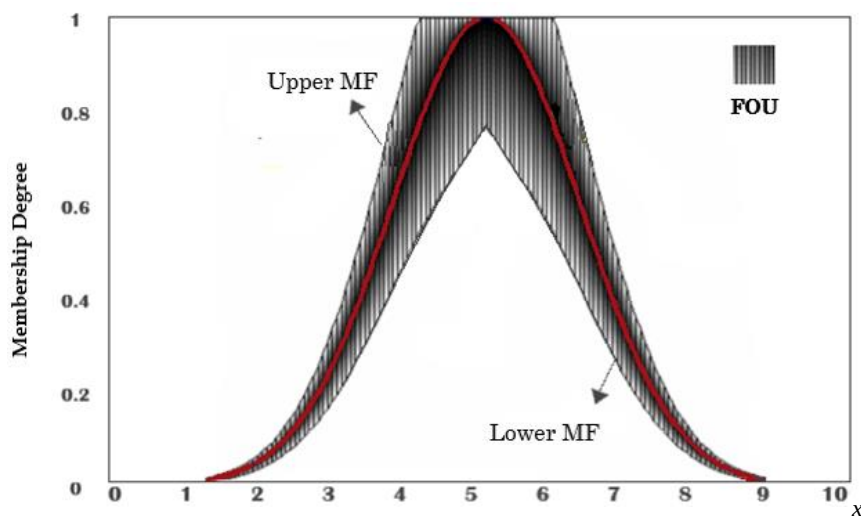


Figure 3.6 : The FOU of interval type-2 Gaussian MF.

The FOU of an IT2FS is described in terms of membership functions (upper and lower MF) as:

$$\text{FOU}(\tilde{\tilde{A}}) = \bigcup_{x \in X} [\underline{\mu}_{\tilde{\tilde{A}}}(x), \overline{\mu}_{\tilde{\tilde{A}}}(x)]$$

if X is discrete, the statement is modified to,

$$\text{FOU}(\tilde{\tilde{A}}) = \bigcup_{x \in X} \{\underline{\mu}_{\tilde{\tilde{A}}}(x), \dots, \overline{\mu}_{\tilde{\tilde{A}}}(x)\}$$

In the (X) , the ‘....’ notation point out all the embedded T1FSs between the upper and lower membership functions (Mendel, 2007).

The membership grade of every domain point is a crisp set in an IT2FS whose domain is some interval contained in $[0,1]$ and in which the third dimension is a constant value (Castillo and Melin, 2008).

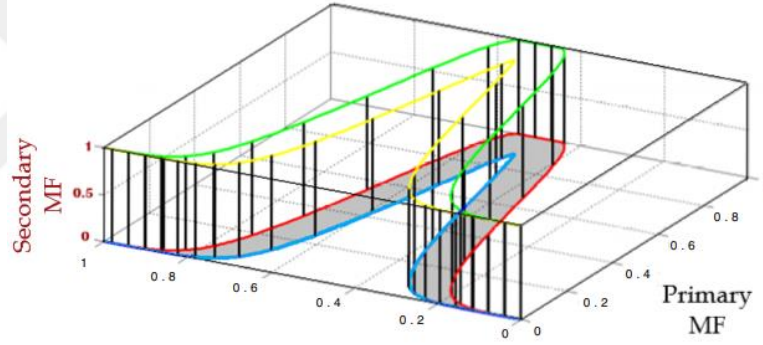


Figure 3.7 : Three dimensional visuals of an IT2FS.

After having briefly expressed about the IT2FS and T2FS, the definitions of mathematical operations and step-by-step developments of T2FS and IT2FS are presented below:

Definition 1: A type-2 fuzzy set $\tilde{\tilde{A}}$ in the universe of discourse X can be characterized by a type-2 membership function $\mu_{\tilde{\tilde{A}}}(x, u)$, where J_X denotes an interval in $[0, 1]$ and $0 \leq \mu_{\tilde{\tilde{A}}}(x, u) \leq 1$ is defined as below:

$$\tilde{\tilde{A}} = \{(x, u), \mu_{\tilde{\tilde{A}}}(x, u) | \forall x \in X, \forall u \in J_X \subseteq [0, 1], 0 \leq \mu_{\tilde{\tilde{A}}}(x, u) \leq 1\}$$

In addition, the type-2 fuzzy set $\tilde{\tilde{A}}$ is also represented as follows when the elements of the fuzzy numbers are continuous (Mendel et al, 2006):

$$\tilde{A} = \int_{x \in X} \int_{u \in J_X} \mu_{\tilde{A}}(x, u) / (x, u) = \int_{x \in X} \left(\int_{u \in J_X} \mu_{\tilde{A}}(x, u) / u \right) / x$$

where $J_X \subseteq [0,1]$ and $\iint$ denotes union over all admissible x and u .

Definition 2: Let $\tilde{A}$ be a type-2 fuzzy set in the universe of discourse X characterized by the type-2 membership function $\mu_{\tilde{A}}(x, u)$. If all $\mu_{\tilde{A}}(x, u) = 1$, then $\tilde{A}$ is called as an interval type-2 fuzzy set and defined as below (Castillo and Melin, 2008; Mendel et al, 2006):

$$\tilde{A} = \int_{x \in X} \int_{u \in J_X} 1 / (x, u) = \int_{x \in X} \left(\int_{u \in J_X} 1 / u \right) / x ,$$

where $J_X \subseteq [0,1]$.

Definition 3: The IT2FS can also be defined as a trapezoidal interval type-2 fuzzy set in the universe of discourse $X = [0, 1]$.

A trapezoidal interval type-2 fuzzy set:

$$\tilde{A}_i = (\tilde{A}_i^U, \tilde{A}_i^L) = \left((a_{i1}^U, a_{i2}^U, a_{i3}^U, a_{i4}^U; H_1(\tilde{A}_i^U), H_2(\tilde{A}_i^U)), (a_{i1}^L, a_{i2}^L, a_{i3}^L, a_{i4}^L; H_1(\tilde{A}_i^L), H_2(\tilde{A}_i^L)) \right)$$

where $\tilde{A}_i^U$ and $\tilde{A}_i^L$ are type-1 fuzzy sets, $a_{i1}^U, a_{i2}^U, a_{i3}^U, a_{i4}^U, a_{i1}^L, a_{i2}^L, a_{i3}^L$ and a_{i4}^L are the reference points of the interval type-2 fuzzy $\tilde{A}_i$; $H_j(\tilde{A}_i^U)$ represents the membership value of the element $a_{i(j+1)}^U$ in the upper trapezoidal membership function, $\tilde{A}_i^U$; $1 \leq j \leq 2$, $H_j(\tilde{A}_i^L)$ represents the membership value of the element $a_{i(j+1)}^L$ in the lower trapezoidal membership function $\tilde{A}_i^L$; $1 \leq j \leq 2$, $H_j(\tilde{A}_i^L)$,

$$H_1(\tilde{A}_i^U) \in [0,1], H_2(\tilde{A}_i^U) \in [0,1], H_1(\tilde{A}_i^L) \in [0,1], H_2(\tilde{A}_i^L) \in [0,1] \text{ and } 1 \leq i \leq n.$$

In this thesis, a hybrid method utilising the IT2FSs to cope with fuzzy multiple attribute group decision-making problems is presented. In the model, the reference points and the heights of the upper and the lower membership functions of the IT2FSs are characterised as trapezoidal IT2FSs. Accordingly, Figure 3.8 depicts the trapezoidal interval type-2 fuzzy set, below.

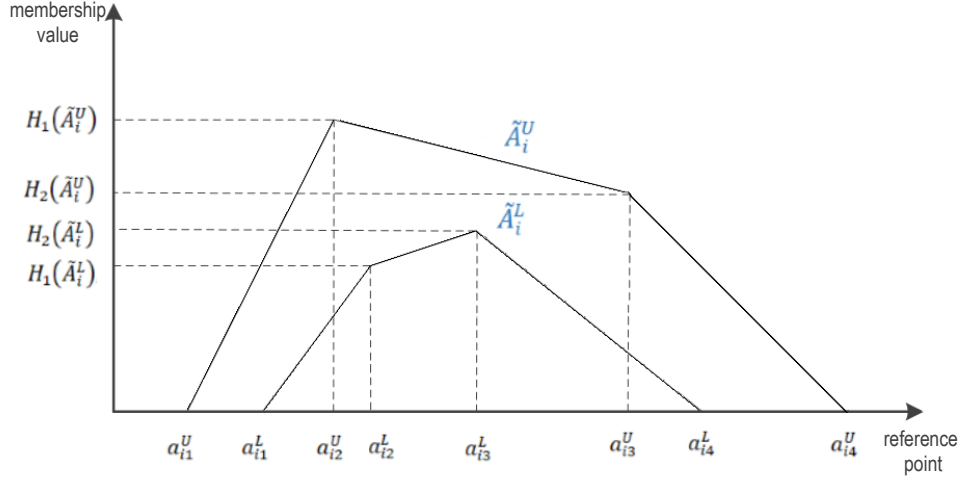


Figure 3.8 : The trapezoidal membership functions of IT2FS.

In this context, trapezoidal MFs have been utilised extensively and frequently especially in real-time implementations with respect to their computational efficiency (Akyuz and Celik, 2016; Castillo and Melin, 2008; Mendel et al, 2006).

Definition 4: To rank and defuzzify the IT2FSs an extended center of area method is utilized. Accordingly, equation (3.3) is applied for the defuzzification process of the IT2FSs. Then, *Defuzzified* $(\tilde{\tilde{A}}_i)$ is defined as below:

$$\tilde{\tilde{A}}_i = \frac{\frac{(a_{i4}^U - a_{i1}^U) + (H_1(\tilde{A}_i^U) * a_{i2}^U - a_{i1}^U) + (H_2(\tilde{A}_i^U) * a_{i3}^U - a_{i1}^U)}{4} + a_{i1}^U + \frac{(a_{i4}^L - a_{i1}^L) + (H_1(\tilde{A}_i^L) * a_{i2}^L - a_{i1}^L) + (H_2(\tilde{A}_i^L) * a_{i3}^L - a_{i1}^L)}{4} + a_{i1}^L}{2} \quad (3.3)$$

For further calculations, mathematical operations to be utilized between two IT2FSs are given below, respectively:

$$\tilde{\tilde{A}}_1 = (\tilde{A}_1^U, \tilde{A}_1^L) \text{ and } \tilde{\tilde{A}}_2 = (\tilde{A}_2^U, \tilde{A}_2^L),$$

$$\tilde{\tilde{A}}_1 = \left((a_{11}^U, a_{12}^U, a_{13}^U, a_{14}^U; H_1(\tilde{A}_1^U), H_2(\tilde{A}_1^U)), (a_{11}^L, a_{12}^L, a_{13}^L, a_{14}^L; H_1(\tilde{A}_1^L), H_2(\tilde{A}_1^L)) \right)$$

$$\tilde{\tilde{A}}_2 = \left((a_{21}^U, a_{22}^U, a_{23}^U, a_{24}^U; H_1(\tilde{A}_2^U), H_2(\tilde{A}_2^U)), (a_{21}^L, a_{22}^L, a_{23}^L, a_{24}^L; H_1(\tilde{A}_2^L), H_2(\tilde{A}_2^L)) \right)$$

The addition operation:

$$\tilde{\tilde{A}}_1 \oplus \tilde{\tilde{A}}_2 = (\tilde{A}_1^U, \tilde{A}_1^L) \oplus (\tilde{A}_2^U, \tilde{A}_2^L) \quad (3.4)$$

Accordingly, equation (3.4) is denoted as below:

$$= \left(\left(a_{11}^U + a_{21}^U, a_{12}^U + a_{22}^U, a_{13}^U + a_{23}^U, a_{14}^U + a_{24}^U; \min(H_1(\tilde{A}_1^U), H_1(\tilde{A}_2^U)), \min(H_2(\tilde{A}_1^U), H_2(\tilde{A}_2^U)) \right), \right. \\ \left. \left(a_{11}^L + a_{21}^L, a_{12}^L + a_{22}^L, a_{13}^L + a_{23}^L, a_{14}^L + a_{24}^L; \min(H_1(\tilde{A}_1^L), H_1(\tilde{A}_2^L)), \min(H_2(\tilde{A}_1^L), H_2(\tilde{A}_2^L)) \right) \right)$$

The subtraction operation:

$$\tilde{A}_1 \ominus \tilde{A}_2 = (\tilde{A}_1^U, \tilde{A}_1^L) \ominus (\tilde{A}_2^U, \tilde{A}_2^L) \quad (3.5)$$

Accordingly, equation (3.5) is denoted as below:

$$= \left(\left(a_{11}^U - a_{21}^U, a_{12}^U - a_{22}^U, a_{13}^U - a_{23}^U, a_{14}^U - a_{24}^U; \min(H_1(\tilde{A}_1^U), H_1(\tilde{A}_2^U)), \min(H_2(\tilde{A}_1^U), H_2(\tilde{A}_2^U)) \right), \right. \\ \left. \left(a_{11}^L - a_{21}^L, a_{12}^L - a_{22}^L, a_{13}^L - a_{23}^L, a_{14}^L - a_{24}^L; \min(H_1(\tilde{A}_1^L), H_1(\tilde{A}_2^L)), \min(H_2(\tilde{A}_1^L), H_2(\tilde{A}_2^L)) \right) \right)$$

The multiplication operation:

$$\tilde{A}_1 \otimes \tilde{A}_2 = (\tilde{A}_1^U, \tilde{A}_1^L) \otimes (\tilde{A}_2^U, \tilde{A}_2^L) \quad (3.6)$$

Accordingly, equation (3.6) is denoted as below:

$$= \left(\left(a_{11}^U \times a_{21}^U, a_{12}^U \times a_{22}^U, a_{13}^U \times a_{23}^U, a_{14}^U \times a_{24}^U; \min(H_1(\tilde{A}_1^U), H_1(\tilde{A}_2^U)), \min(H_2(\tilde{A}_1^U), H_2(\tilde{A}_2^U)) \right), \right. \\ \left. \left(a_{11}^L \times a_{21}^L, a_{12}^L \times a_{22}^L, a_{13}^L \times a_{23}^L, a_{14}^L \times a_{24}^L; \min(H_1(\tilde{A}_1^L), H_1(\tilde{A}_2^L)), \min(H_2(\tilde{A}_1^L), H_2(\tilde{A}_2^L)) \right) \right)$$

The arithmetic operation:

$$k \tilde{\tilde{A}}_1 = \left(\left(k \times a_{11}^U, k \times a_{12}^U, k \times a_{13}^U, k \times a_{14}^U; H_1(\tilde{A}_1^U), H_2(\tilde{A}_1^U) \right), \right. \\ \left. \left(k \times a_{11}^L, k \times a_{12}^L, k \times a_{13}^L, k \times a_{14}^L; H_1(\tilde{A}_1^L), H_2(\tilde{A}_1^L) \right) \right) \quad (3.7)$$

$$\frac{\tilde{\tilde{A}}_1}{k} = \left(\left(\frac{1}{k} \times a_{11}^U, \frac{1}{k} \times a_{12}^U, \frac{1}{k} \times a_{13}^U, \frac{1}{k} \times a_{14}^U; H_1(\tilde{A}_1^U), H_2(\tilde{A}_1^U) \right), \right. \\ \left. \left(\frac{1}{k} \times a_{11}^L, \frac{1}{k} \times a_{12}^L, \frac{1}{k} \times a_{13}^L, \frac{1}{k} \times a_{14}^L; H_1(\tilde{A}_1^L), H_2(\tilde{A}_1^L) \right) \right) \quad (3.8)$$

3.3 Fault Tree Analysis (FTA)

3.3.1 Overview for FTA technique

FTA (Lee et al, 1985) is one of the most crucial logic and probabilistic techniques extensively using for reliability evaluation and probabilistic risk assessment of complex systems (Kornecki and Liu, 2013; Mentis and Helvacioğlu, 2011; Pan and

Yun, 1997; Chen et al, 1995). In the context of risk analysis, this fault identification technique is applied to evaluate the level of risk posed by all potential identified hazards in the system. As a top-down and deductive failure analysis (Wang et al, 2020; Khan and Abbasi, 2000; Kirwan, 1994) the technique identifies the sub-systems which are essential for the operation of a complex system (Kristiansen, 2005). Several sequential and parallel combinations of faults which will cause the undesired event called the top event (TE) are depicted at different levels of system decomposition. The failure probability of each system must be obtained to find all pathways in which the undesired event (TE) can occur. However, a fault tree is focused on the top event of the tree and only includes faults that lead to this undesired top event. Herewith, the fault tree is a graphic model representing the logical interrelationships of basic events (BE) and employs Boolean algebra as well. Boolean algebra rules are applied to attain one form of the fault tree, called the minimal cut set form that allows qualitative and quantitative assessments to be performed in a straightforward manner (Vesely, 2002). Only binary operational modes are assumed in a fault tree (Kristiansen, 2005). Namely, the event either occurs or does not occurs.

The visualization of a conventional FTA is based on events, logical gates and symbols (Kristiansen, 2013). In a fault tree, events are identified by their failure probabilities. Accordingly, logical gates are utilized to represent the relationships of events. In that case, a higher event is the “output” of the gate while a lower event is the “input” of the gate. To sum up, the gate expresses the relationship type of the input events needed for the output event.

The prevalent symbols used in FTA are illustrated as below in Table 3.1, Table 3.2, and Table 3.3, respectively:

Table 3.1 : Transfer symbols of fault tree.

Transfer Symbol	Transfer Name	Meaning of Symbol
	Transfer In	Signifies that the fault tree is developed further at the occurrence of the corresponding Transfer Out
	Transfer Out	Signifies that this portion of the fault tree must be attached at the corresponding Transfer In

Table 3.2 : Event symbols of fault tree.

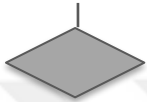
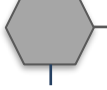
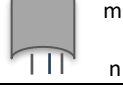
Event Symbol	Event Name	Meaning of Event
	Undesired Event (Top Event)	Specifies an event that constitutes the top event in a fault tree diagram and generally consisting of a complete and catastrophic failure.
	Basic Event	Signifies a basic initiating fault event that requires no more development
	Conditional Event	Signifies a specific conditions or restrictions that can apply to any logic gate
	Undeveloped Event	Signifies an event that is no further developed due to information is unavailable or due to it is of insufficient consequences
	House Event	Signifies an event that is normally expected to occur
	Intermediate Event	Signifies a fault event which occurs due to one or more antecedent causes acting through logic gates

Table 3.3 : Gate symbols of fault tree.

Gate Symbol	Gate Name	Correlation
	AND Gate	The output event occurs only if all input events occur concurrently
	OR Gate	The output event occurs only if any one of the input events occurs
	Inhibit Gate	Input produces output when conditional events occur and the output is caused by a single input
	Priority AND Gate	The output event occurs only if all input events occur in the determined specific sequence
	Exclusive OR Gate	The output event occurs only if exactly one of the input events occur
	'm' out 'n' gate	The output event occurs only if 'm' out of 'n' input events occur

Besides being a qualitative model, a fault tree can be analysed both quantitatively and qualitatively. However, the nature of the model itself is qualitative (Vesely et al, 1981).

The general construction procedures of Fault Tree Analysis to be applied can be stated step by step as follows:

Step 1: Identify the system of interest

Step 2: Identify the undesirable event called as Top Event (TE)

Step 3: Determine the events (i.e., Basic Events (BE) and Intermediate Events (IE)) and conditions which directly lead to the TE.

Step 4: Determine the events and conditions which directly lead to each IE and repeat the process until the Fault Tree Model is all complete.

Step 5: Solve the Fault Tree Model to determine all the possible combinations of events that contribute to the TE.

Step 6: Identify crucial dependent failure potentials among events, examine the fault tree model and the list of minimal cut sets (MCS)

Step 7: Perform analysis (quantitative if necessary) to predict future performance for the system

Step 8: Determine the risks associated with the most important vulnerabilities in the system and make efficient recommendations to reduce the risks.

The quantitative assessments of a fault tree consist of the determination of TE probabilities and importances of BEs (Vesely, 2002). The quantitative approach of the FTA utilizes the failure probability (q_i) of the BEs and the gates to calculate the TE's probability (Q_0). Intermediate gate event ("AND" or "OR") probabilities are calculated from the base of the tree and running upwards till the top event probability is attained (Ugurlu et al, 2015). Additionally, the minimal cut sets of the Fault Tree are established. A minimal cut set (MCS) is utilized to specify the structural vulnerability of the system (Akyuz et al, 2020).

According to gate event, the equations are utilized to obtain the occurrence probability of the top event, where t denotes the probability of occurrence at time ' t ', n denotes the number of the basic events (BEs) and j denotes the occurrence probability of MCS at the time ' t '.

At this point, for an "AND" gate event;

$q_1(t) = P(E_1(t))$ and the occurrence probability of the top event is denoted as in equation (3.9) and (3.10) below:

$$Q_0(t) = P(E_1(t) \cap E_2(t)) \quad (3.9)$$

$$Q_0(t) = \prod_{j=1}^n q_i(t) \quad (3.10)$$

As for an "OR" gate event;

$q_1(t) = P(E_1(t))$ and the occurrence probability of top event is denoted as in equation (3.11) and (3.12) below:

$$Q_0(t) = P(E_1(t) \cup E_2(t)) = P(E_1(t)) + P(E_2(t)) - E_1(t) \cap E_2(t) \quad (3.11)$$

$$Q_0(t) = 1 - \prod_{j=1}^n (1 - q_j(t)) \quad (3.12)$$

Each cut set in the system involves one unique set of BEs, which by occurring simultaneously trigger the TE (Kristiansen, 2005). The measure of importance for each BEs may be calculated due to the BEs are present in several cut sets. Accordingly, the importance rank of the MCS rather crucial during the occurrence of the top event. Following equations (equation 3.13 and 3.14) are utilised for MCSs (Arici et al, 2020; Kuzu et al, 2019; Lavasani et al, 2015).

$$TE = MCS_1 + MCS_2 + \dots + MCS_N = \bigcup_{i=1}^{n_c} MCS \quad (3.13)$$

Based on this, the following operations are utilised to calculate the TE occurrence probability:

$$\begin{aligned} P(T) &= P(MCS_1 \cup MCS_2 \cup \dots \cup MCS_N) \\ &= P(MCS_1) + P(MCS_2) + \dots P(MCS_N) - (P(MCS_1 \cap MCS_2) \\ &\quad + P(MCS_1 \cap MCS_3) + \dots P(MCS_i \cap MCS_j) \dots) \dots \\ &\quad + (-1)^{N-1} P(MCS_1 \cap MCS_2 \cap \dots \cap MCS_N) \end{aligned} \quad (3.14)$$

In the FTA method, the Fussell-Vesely Importance Measure (I^{FV}) is applied to ascertain the significance value of BEs and MCSs constructing the top event (Shafiee et al, 2019). Given that, at least one MCS comprises the BE (i) is failed at (t), when the TE is triggered at the time (t). By the equation (3.15), the probability above can be calculated:

$$I_i^{FV}(t) = \frac{Q_i(t)}{Q_0(t)} \quad (3.15)$$

Where I_i specify the importance degree of MCS, $Q_i(t)$ is specify the probability of which one MCS containing the BE (i) is failed at the time (t) and $Q_0(t)$ is specify the probability of occurrence for the TE in all MCS (Aydin et al, 2021).

FTA covers the most reliable faults as evaluated by the domain experts. The faults can be events that are related to hardware, software or equipment failures, environmental events, human errors or any events leading to the undesired event (Vesely, 2002). The investigations of human error play a considerable role in the construction of fault trees. In the case of the assessment of human error contribution to risk, attention has to be taken to comprehend the dependence of all human actions on one another. Once errors have been determined, the contribution of each error to the total level of risk in the system is ascertained. This provides the experts, improve detailed risk-reduction measures when required.

3.3.2 Overview for application of FTA

The approach was originally developed by H.S. Watson in 1962 under a U.S. Air Force Ballistics Systems Division contract to assess the Minuteman I Intercontinental Ballistic Missile (ICBM) Launch Control System at Bell Telephone Laboratories in the USA. Today, the FTA method is used in widespread domains such as aerospace (Vesely, 2002), aviation (Oriola and Adekunle, 2015; Kornecki and Liu, 2013; Wong and Yeh, 2007), chemical process (Khan and Abbasi, 2000), pharmaceutical (Rath, 2008) and petrochemical (Lavasani et al, 2015).

The expanding volume of global trade and the increasing worldwide shipping traffic causes a rise in maritime accidents and loss of life (Baalisampang et al, 2018). There have been some significant studies that utilized the FTA-based technique to identify and evaluate risks in the maritime industry. For instance, the study utilising the Fuzzy

Fault Tree Analysis (FFTA) technique was conducted by Mentis and Helvacioğlu (2011) to combine the effects of operational failures and human errors for analysing the risks of tanker buoy spread mooring systems. The FFTA method was found more flexible and applicable than conventional FTA for fault identification and hazard estimation of spread mooring systems. Likewise, Kuzu et al. (2019) utilised the FFTA to perform systematic risk analysing on the case of ship mooring operation. In the study, a real maritime accident is examined considering potential risks.

Uğurlu et al. (2015) used the FTA technique to carry out risk assessments for collision and grounding cases that occurred in oil tankers. In the paper, the potential problems that cause the collision and grounding accidents are determined and the significance degree of the initial events causing the occurrence of accidents are determined with causal factors by the FTA method. Similarly, the other study was conducted by Antao and Soares (2006) to identify hazards related to casualties of Ro-Pax vessels. The identification of the basic events (BEs) that cause to specified accident, the performance requirements and the modelling of the interrelation between the relevant events are carried out utilising FTA. Li et al. (2011) conducted a detailed review and assessment of various quantitative risk assessment models for maritime waterways. FTA method was evaluated as practicable and useful for modelling the errors related to human performance and the errors related to incapacitation. Akyuz et al. (2020) conducted a comprehensive risk analysis by using the bow-tie method that consists of FTA and ETA within a fuzzy logic environment. The cargo liquefaction operation onboard ship is selected as a case study due to the operation is extremely hazardous for the crew, ship and marine environment and has high risks. The method is utilized to focus on the causes and consequences of an event throughout the operation.

3.4 Proposed Approach: FTA Structure under IT2FS-SLIM

The scarce data for human error in containership cargo operations is the motivation for developing the methodological extension through the integration of the IT2FS based SLIM technique into the FTA structure. Accordingly, the conceptual framework of the proposed approach for an empirical HEP and human error contribution to risk for containership cargo operations to enhance safety and operational reliability in the maritime transportation industry is depicted in Figure 3.9.

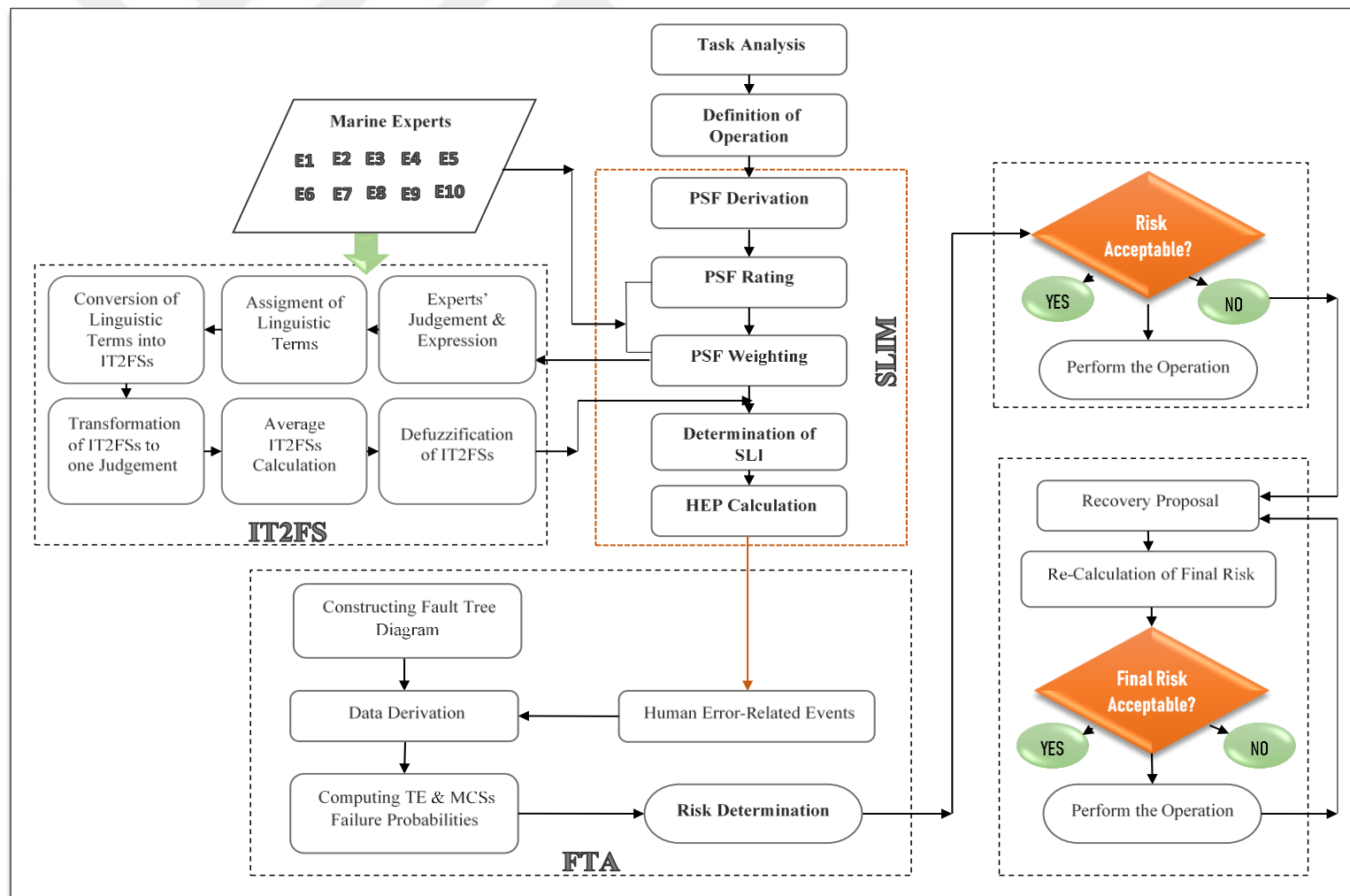


Figure 3.9 : The conceptual framework of the integration.

Step 1- Task analysing: In the first step of the hybrid approach, an extensive task analysis is performed to identify the main tasks. The task analysis expresses relevant activities that the crew has to carry out during loading operation on-board ship. In this context, a hierarchical task analysis is carried out to perform meticulous analysis for sub-tasks of the main tasks of the work (Shepherd, 2001). HTA is rather convenient to identify each task in terms of its goals. Besides identifying tasks carried out by people, HTA is also capable of producing a systems analysis (Stanton, 2006). HTA may involve pre-activities, activities, and post-activities in compliance with the operation. Accordingly, the HEP value of each sub-task can be calculated, and thus, combining each of them provides the final HEP value.

Step 2- Definition of Operation: Having completed the task analysis, the real-time containership loading operation is explained in light of the various conditions such as physical working conditions, port facility instructions...etc. Each process of operation including day time, sea state, weather condition, and interruptions of operation related to port facilities or vessel will be defined from the berthing instruction to completion of the operation, in detail. These conditions may lead to human error and increase HEP during the carrying out of the specific task of the operation.

Step 3- PSF Derivation: PSFs that are of paramount effect upon human performance are obtained by domain experts for the relevant operation. These relative factors which are any factors relating to the task, individuals, or working environment are specifically identified such as crew experiences, training, familiarity with task, workload, stress and safety culture of the ship management...etc.

Step 4- PSF Rating: In light of the determined PSFs, the marine experts nominate a value from 1 to 9 on a linear scale where 1 specifies a remarkable impact upon the crew performance for the relevant task. This means that in case the PSF has a considerable influence on the task, 1 is assigned as the highest value. In other words, 9 is the correct value to be assigned if that PSF has the lowest importance on the task. Because of their negative or positive effect, each PSF, may increase or decrease the HEP value in a specific task. To give an example, being inexperienced in a task, may lead to stress on seafarers and force them to make errors.

Step 5- PSF Weighting: Each of the PSFs to trigger human error has a different influence on each specific task. Accordingly, the values to be nominated to PSFs may

vary from one expert to the other. The weighting of PSFs is in a percentage value-form in the traditional SLIM. Further, the experts weigh the PSFs subjectively in the basic SLIM. At this point, IT2FS convert the marine experts weighting assessments into linguistic variables and then acquire the crisp values by utilizing equation (3.3), (3.4), (3.5), (3.6), (3.7), and (3.8) for the representation of percentage value. In this way, the weakness of the experts' assessments upon PSF is minimized and the accuracy of outcomes is maximized.

Step 6- Determination of SLI: Right after all rating and weighting values are obtained, the success likelihood index (SLI) value is calculated by utilizing equation (3.1) in this step. The index provides predicting the cases in which several human errors may occur.

Step 7- HEP Calculation: In this step of the approach, the calculated SLI values are transformed into HEP values as notated in equation (3.2). In the equation, a and b are the constant values and the SLI values are calibrated in order to identify them. The conversion of the SLI values to HEP is achieved by a logarithmic relationship. The Linear logarithmic function with base 10 (log base 10) (Chien et al, 1988) is the foundational aspect of the process. At this point, to calibrate the SLI, the HEP values of a minimum of two tasks should have been attained.

Step 8- Risk Determination: As the last step, FTA is carried out under IT2F based SLIM to evaluate how the human errors (HEs) increase the operational risks as well as to determine whether the final risk value is acceptable. The IT2F based SLIM approach quantifying HEPs provides probabilistic outcomes for risk analysis in a case. The HEP values acquired by using the IT2F-SLIM steps are incorporated into the fault tree. Based on the outcomes, the failure probability of each human error-related BE is calculated. Thereby, the occurrence probability of the undesired event (TE) is calculated for detailed risk analysis.

According to the comprehensive analysis result, the criticality of the operational activities is evaluated based on the potential human error contribution. In case the final risk value is acceptable, the operation is carried out. However, if the final risk level is determined unacceptable, recovery proposals are recommended to reduce the final risk. Proper mitigation precautions are also taken for PSFs that may cause increase HEP values. Accordingly, the final risk value is re-calculated. In the case the final risk

value revealed in acceptable limits, the operation is carried out. If the re-calculated final risk value is not reduced to an acceptable limit, the recovery proposals are revised, mitigation precautions are re-taken and the final risk is re-calculated once again.



4. QUANTITATIVE ASSESSMENT OF HEP

This chapter involves a meticulous real-time cargo handling operation onboard container ship to demonstrate the hybrid approach quantifying human error probability since shipping operations have potential risks for human life, port facilities and the marine environment. In this context, containerization and cargo loading operation process are the points extensively emphasized respectively to emphasize the importance of the case. This chapter also introduces a system application that is defined step by step in the previous chapter.

4.1 Containerization in Global Maritime Trade

Container transportation makes it possible to transfer towering quantities of goods at a time thereby containerization has become even more important for global maritime trade in recent years. As of today, containerized trade accounted for approximately 24.0 per cent of international maritime trade and millions of containers are used globally because of being an efficient transportation method. Because of the increasing demand and increasing Cargo carrying capacity in the global maritime market, the container vessels fleet achieve growth continuously. In 2019, the container fleet continued to increase (app. 5 per cent) all over the world in comparison with the chemical tanker, dry bulk carriers and oil tanker. While stable growth was observed for chemical tanker and dry bulk carrier and a downward trend was observed for the oil tanker (UNCTAD, 2019). Additionally, containerships have become more technologically advanced and fuel-efficient day by day.

Global containerized trade met with major uncertainty, in 2018. New IMO regulations (URL-1) imposing a sulphur cap on bunker fuels, commercial frictions, weakness in consumer markets and negative developments in the world economy caused containerized trade volumes to expand at a much slower rate than in 2017. However, volumes, as measured in TEUs, increased by 5.6 per cent in 2019 and bringing the World total of approximately 160,5 million. The containerized trade data between 2016 and 2019 are given below in Table 4.1:

Table 4.1 : Containerized trade data between 2016 and 2019 years.

Routes	Million 20-foot equivalent units (TEUs)			
	2016	2017	2018	2019
Mainlane East–West	54 845 031	57 950 975	60 721 427	63 710 784
Others Total; (North South South South Intraregional)	84 802 064	90 097 054	91 236 532	96 744 144
World Total	139 647 095	148 048 029	151 957 959	160 454 928

According to the data above, the annual percentage change is recorded as 2.5 per cent in 2016, 6.0 per cent in 2017, 2.6 per cent in 2018 and 5.6 per cent in 2019, respectively. It is expected to grow at a compound annual growth rate of 4.5 per cent over the 2019–2024 period according to UNCTAD (2019) and 4.6 per cent over 2017–2026 according to Lloyd's List Intelligence research (URL-2).

4.2 Container Units

Container units are an integral part of maritime transportation because of handling various kinds of goods in vary dimensions and materials in safe. All types of shipping containers are manufactured, tested, and certified by the International Organization for Standardization (ISO). The standard covering the coding, identification and marking of intermodal containers is ISO 6346:1995 that adopted in January 1996 (URL-3). The standard is maintained and managed by the Bureau of International Containers (BIC). It provides an identification system for every shipping container involving an owner/operator code (three letters), equipment category identifier (one letter), a serial number (six Arabic numerals) and checks digit (one numeral) as well operational marks (ISO 6346, 1995E). Thus, container units become unique and suitable for multiple transportations via containership, rail or truck. In addition, this identification code of containers facilities international circulation and temporary admission for custom operations. It also provides the control of containers, manually/automatically by computerised or remote-control systems at any step of the transportation chain. Today, different types of container units are being handled to meet maritime transport demand. These ISO container units vary according to their dimension, construction and handling property. ISO containers are manufactured in a certain standard size to transport freight.

The most commonly utilised are 20' (twenty-foot equivalent unit-TEU), 40' (forty-foot equivalent unit- FEU), 40' HC (High Cube), 45' HC (High Cube) and 48' by dimensions in maritime transport. Additionally, 8', 10', 53' and 60' shipping containers are available that are mostly used for rail and road transportation. The details of ISO containers that commonly preferred in maritime transportation are mentioned below in Table 4.2.

Table 4.2 : External dimensions of most commonly used ISO containers.

Dimension	Standart				High Cube					
	20'		40'		40' HC		45' HC		48' HC	
	<i>Feet</i>	<i>Meter</i>	<i>Feet</i>	<i>Meter</i>	<i>Feet</i>	<i>Meter</i>	<i>Feet</i>	<i>Meter</i>	<i>Feet</i>	<i>Meter</i>
Lenght	20' 0"	6.10	40' 0"	12.19	40' 0"	12.19	45' 0"	13.72	48' 0"	14.63
Width	8' 0"	2.44	8' 0"	2.44	8' 0"	2.44	8' 0"	2.44	8' 6"	2.59
Height	8' 6"	2.59	8' 6"	2.59	9' 6"	2.90	9' 6"	2.90	9' 6"	2.90

The usable capacity of a twenty-foot container is 33.2m³, the container's empty weight is 2,200 kg, and the maximum weight that can be loaded is 28,200 kg in theory.

A forty-foot container's usable capacity is 67,6 m³. The empty weight of the container is 3,800 kg, and the maximum weight that can be loaded is 26,600kg.

A forty-foot HC container's usable capacity is 75,3 m³. The empty weight is 3.900 kg, and the maximum weight that can be loaded is 26,580 kg.

A forty five-foot HC container's usable capacity is 86,1 m³. Empty weight is 4.800 kg, and the maximum weight that can be loaded is 25,600 kg in theory.

The last ISO container commonly used is a forty eight-foot (Tank for Gas) container. The container's usable capacity is 97.6 m³. The empty weight is 4.950 kg, and the maximum weight that can be loaded is 25,520 kg. However, the number of goods that can be loaded would depend on several factors such as restrictions of the shipping line, the specific feature of the goods...etc.

The ISO standard 45ft HC container with all complementary markings such as identification number, size and type code, owner's logo and various operational marks is depicted in Figure 4.1 below:

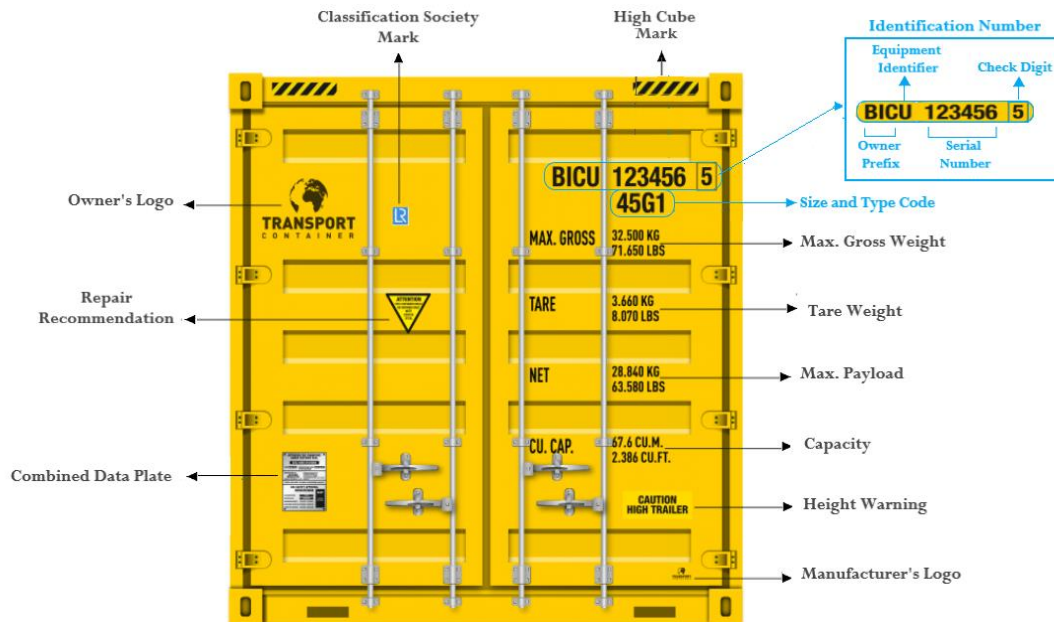


Figure 4.1 : An ISO standart 45ft HC container with markings.

In conjunction with BIC Code, The Convention for Safe Containers (CSC, 1972) requires that a container used for international transport must be fitted with a valid safety approval plate. The plate, called as CSC Plate, is fitted to all shipping containers at the time of manufacture and is riveted to the left door of the container. Once containers are approved, they are easily able to move in international transportation with the minimum of safety control formalities.

The 1972 Convention for Safe Containers adopted by a conference jointly convened by the United Nations and IMO, includes Annex I and Annex II. Annex I includes regulations for the testing, inspection, approval and maintenance of containers whilst Annex II covers structural safety requirements and tests, including details of test procedures. The convention mainly focuses on two goals: i) To maintain a high level of safety of human life in the transport and handling of containers ii) To facilitate the international transport of containers by providing international safety regulations.

Standard containers have been manufactured to meet the demands of importers and exporters in the marine trade. Different shipping container types enable possible to handle nearly all sizes and types of goods. Different forms of shipping containers in use today are identified below, respectively.

General Purpose Container: They are the most recognised containers in use today. They are rather useful because they are strong, watertight and durable for the transportation of goods. The general-purpose containers are in 10ft, 20ft and 40ft

dimensions. They are divided into two types with ventilation type and non- ventilation type. Non- ventilation type has passive vents at the upper part of the cargo space. With ventilation, the type has a non-mechanical system. They have vents in the lower and upper parts of the cargo space. Some of with ventilation types has also mechanical ventilation systems located internally/externally.

Ventilated Container: The 20 feet ventilated container enable air circulation because of having lateral openings. They are rather favourable for the transportation of goods requiring constant temperature. The ventilation system expels hot air and permits airflow, therefore, prevents condensation and humidity changes. Coffee is the most-known product transported in a 20ft ventilated container.

Dry Bulk container: They are widely used for transporting raw materials such as grain, powder or sand in large, unpackaged parcels. They are loaded from the top and discharged from the bottom and they are completely closed, airtight, and non-pressurized.

Flat Rack container: These shipping containers are simple storage containers having collapsible sides that can be folded to make a flat rack for the handling of a wide range of goods. They are favourable for handling oversize goods such as construction products and heavy machinery, and the sides are rather durable to allow cargo securing.

Open Top container: This type of container has a convertible top that can be completely removed. This property makes them favourable for goods that are over-height in terms of can not be easily handled through the doors of the container. Open top containers are in 20ft and 40ft dimensions and they have lashing rings to secure cargo. Tall machinery and heavy finished products are cargoes that can only be handled with open-top containers.

Platform Container: Platform containers with incomplete superstructure are used for handling oversized and weighty goods especially. They only consist of a floor structure with a high loading capacity. The durable structure enables to concentrate heavy weights on certain areas. They do not have any side or end walls and they are in 20ft and 40ft dimensions. Platform-based containers with complete superstructure have open ends (skeletal).

Named-Cargo Container: Some of them are a type of platform-based container and mainly used as a car carrier, live fish carrier, livestock carrier, They are the units especially preferred for shipment of cargoes over a long distance. They have collapsible sides that provide a cargo fit inside the containers without the risk of being damaged or moved.

Refrigerated Container: The ISO shipping container called Reefer is used to transport temperature-sensitive products such as vegetables, meat, fruits that need to be maintained at a certain temperature to protect freshness. The Reefer Containers are powered by a ship generator providing electricity to maintain any temperature regulated between -30°C and $+30^{\circ}\text{C}$. They are generally in 20 ft and 40 ft dimension and rather expensive due to power and maintenance requirements.

Insulated Container: They are a type of thermal containers that come with a regulated temperature control allowing them to maintain a higher temperature. They enable to transport of temperature-sensitive products such as foods, pharmaceuticals, biological materials, and chemicals. They are rather favourable for long-distance transportation of good and enable to maintain product freshness and efficacy.

Tank Container: These ISO shipping containers are specially designed for the transportation of liquids and gases. They are mostly made of strong steel or other anti-corrosive materials. They can transport nearly all bulk cargoes ranging from perishable liquids such as oil or wine to hazardous substances. Therefore, they are lined with an insulating material that protects them from the dangerous goods that they transport. An ISO tank container should be tagged with a determined IMO label and other complementary warning marks to transport hazardous (IMDG) goods. Then again, additional requirements need to be fulfilled for handling IMO labelled ISO tanks onboard containerships.

High Cube Container: High Cube containers are in 40ft and 45ft dimensions and similar in structure to general-purpose containers. However, they are 1' higher than 8' 6" and preferred where higher volume is required for a cargo. Most of them have gooseneck chassis that allows them to lie lower and be of taller structure. The HC containers must be marked by a label that consists of sets of black figures on a yellow background, surrounded by a black border. It is mandatory to specify the high cube container.

Half Height Container: These shipping containers are half the height of full-sized containers and they are engineered to carry especially heavy and dense bulk cargoes such as coal, stones and other mined materials. Therefore, they are mostly made of durable steel. Further, because of their lower centre of gravity, they can handle heavier loads than other types of shipping containers. so they are rather preferred in use today. They are generally in 10ft, 20ft, and 24ft dimensions.

An ISO agreement (ISO 6346, Amendment 3) concerning the marking codes to describe length, height and type of shipping container in an easy to read is provided in Table 4.3 to identify the types mentioned above (URL-4).

4.3 Problem Description

Containership cargo operations involve an extensive activity that requests the responsible crew to handle different tasks and keep a caution on other events at the same time. Especially during the operations, some factors may force the responsible crew to forget crucial activities that need to be properly checked. In case exacting attention is not paid during cargo operation, that leads to serious consequences for human life, ship, port facility and the marine environment. Safe container handling, safe and secure stacking and maintaining the ship stability are the focal points and the main objectives from ship berthing at the pier till operation completion in the port. The rate of cargo handling is especially higher in large ports with significant container terminals. This means that a high volume of goods will be handled by different container types onboard ships at once. Although a shorter ship time in port is a positive indicator of the level of port efficiency and quite desired case for ship owners, safe cargo operation is becoming increasingly important for vessels and ports in the face of growing risks. Further, higher precautions need to be implemented to prevent undesired events and to ensure the safety of the crew, ship, and port facility while handling IMDG, reefer, flat rack, OH, and OOG type containers simultaneously. In this case, a lot of pressure is put on the officers and all responsible crew and requires more attention to handle the operation efficiently. At this point, crew performance on given tasks plays a critical role in preventing maritime casualties and loss of life. Therefore, the probability of human error shall be analyzed during the completion of a specific task for the improvement of operational safety.

Table 4.3 : Standard ISO container type identification.

Designation of Type	Code	Group Code	Main Characteristics with Detailed Type Code ^a and Type Code ^b	Unassigned with Detailed Type Code ^a and Type Code ^b
General Purpose Container (Without ventilation)	G	GP	Opening(s) at one end or both ends, G0-GA Passive vents at upper part of cargo space, G1-GB Opening(s) at one or both ends plus “full” opening(s) on one or both sides, G2 -GD Opening(s) at one or both ends plus “partial” opening(s) on one or both sides, G3-GG With bulk capabilities, G9-GY	(Unassigned) G4-GJ, G5-GM, G6-GV G7-GW, G8-GX
General Purpose Container (With Ventilation)	V	VH	Non mechanical system,vents at lower and upper parts of cargo space V0-VA Mechanical ventilation system, located internally V2-VD Mechanical ventilation system, located externally V4-VJ	(Unassigned) V1-VB, V3 -VG, V5-VM, V6-W, V7-VW, V8 -VX, V9-VY
Dry Bulk Container (Non-pressurized, box type)	B	BU	Closed, B0-BA Airtight, B1-BB Rear discharge/cat flap type, B3-BG Rear discharge/full width opening, B4-BJ Rear discharge/full width fixed, B5-BM Front discharge/full width, B8-BX Side discharge, B9-BY	(Unassigned) B2- BD, B6-BV, B7-BW
Named Cargo Container	S	SN	Livestock carrier, S0 -SA Automobile carrier, S1 -SB Live fish carrier , S2 -SD Generator, S4-SJ	(Unassigned) S3-SG - S5-SM -S6 -SV- S7 -SW- S8-SX -S9-SY
Thermal Refrigerated Container	R	RE	Mechanically Refrigerated, R0-RA	***
Refrigerated and heated	R	RT	Mechanically refrigerated and heated, RI -RB	***

Table 4.3 (continued) : Standard ISO container type identification.

Designation of Type	Code	Group Code	Main Characteristics with Detailed Type Code ^a and Type Code ^b	Unassigned with Detailed Type Code ^a and Type Code ^b
Self-Powered	R	RS	Mechanically refrigerated, R2-RD Mechanically refrigerated and heated, R3-RG	(Unassigned) R4 -RJ, R5-RM, R6-RV, R7-RW, R8-RX, R9-RY
Refrigerated and/or heated with removable equipment	H	HR	Refrigerated and/or heated with removable equipment located externally, heat transfer coefficient K = 0,4 W/(m ² K), H0 -HA Refrigerated and/or heated with removable equipment located internally, H1-HB Refrigerated and/or heated with removable equipment located externally, heat transfer coefficient K = 0,7 W/(m ² -K), H2-HD	(Unassigned) H3-HG, H4-HJ
Insulated	H	HI	Insulated; heat transfer coefficient K = 0,4 W/(m ² -K), H5-HM Insulated; heat transfer coefficient K = 0 W/(m ² -K), H6-HV Opening(s) at one or both ends, U0-UA Opening(s) at one or both ends, plus removable top member(s) in end frames, U1 -UB Opening(s) at one or both ends, plus opening(s) on one or both sides, U2 -UD Opening(s) at one or both ends, plus opening(s) on one or both sides plus removable top member(s) in end frames, U3 -UG Opening(s) at one or both ends, plus partial opening on one side and full opening on the other side, U4-UJ Open topped container with removable hard top U6 -UV Coil carrier, U9-UY	(Unassigned) H7-HW, H8-HX, H9-HY
Open-Top Container	U	UT		(Unassigned) U5-UM , U7-UW, U8-UX
Platform Container	P	PL	Platform, P0-PA	***
Fixed	P	PF	Two complete and fixed ends, P1-PB Fixed posts, either freestanding or with removable top member, P2-PD	***
Folding (collapsible)	P	PC	Folding complete end structure, P3-PG Folding posts, either freestanding or with removable top membe, P4-PJ	***
Complete superstructure	P	PS	Open top, open ends (skeletal), P5-PM	***

Table 4.3 (continued) : Standard ISO container type identification.

Designation of Type	Code	Group Code	Main Characteristics with Detailed Type Code ^a and Type Code ^b	Unassigned with Detailed Type Code ^a and Type Code ^b
For named cargo	P	PT	Ship's gear carrier, P6-PV Car carrier, P7-PW Timber/pipe carrier, P8-PX Coil carrier, P9-PY	**
Pressurized tank container (liquids and gases)	K	KL	Liquid tank non-regulated goods, K0-KA Liquid tank dangerous goods ≤ 2,65 barc pressure, K1-KB Liquid tank dangerous goods >2,65 barc and ≤ 10 barc pressure, K2-KD Liquid tank dangerous goods > 10 barc high pressure, K3-KG Liquid tank non regulated goods requiring power supply, K4-KJ Liquid tank for dangerous goods ≤ 10 barc requiring power supply, K5-KM Liquid tank for dangerous goods > 10 barc pressure requiring power supply, K6 -KV Cryogenic tank, K7-KW Gas tank, K8-KX	(Unassigned) K9-KY
Pressurized and non-pressurized tank container (dry)	N	NH	Hopper type vertical discharge, N0-NA Hopper type rear discharge, N1-NB Non pressurized rear discharge, N3-NG N Non-pressurized side discharge, N4-NJ	**
	N	NN	N Non-pressurized tipping discharge, N5-NM N Pressurized rear discharge, N7-NW N Pressurized side discharge, N8-NX N Pressurized tipping discharge, N9-NL	(Unassigned) N2-ND, N6-NV
Air/surface container	A	AS	A0	A0

4.4 Container Handling

Containerization should be dealt with a set of technical and operational requirements especially related to the following conventions and other mandatory and non-mandatory instruments to maintain a high level of safety of human life and the marine environment in the transportation, stowage and handling of containers.

4.4.1 Operational requirements

International Convention for the Safety of Life at Sea (SOLAS), 1974, International Convention for the Prevention of Pollution from Ships MARPOL 73/78, International Convention for Safe Containers (CSC), 1972, International Maritime Dangerous Goods (IMDG) Code and supplements are the main mandatory instruments dominating any stage of transportation of containers. In addition, Guidelines for the preparation of the Cargo Securing Manual (CSM), Emergency Response Procedures for Ships Carrying Dangerous Goods (EmS Guide), Medical First Aid Guide for Use in Accidents Involving Dangerous Goods (MFAG) are the essential non-mandatory instruments that should be taken into consideration in the transportation of containers.

The SOLAS regulations specify that cargo shall be loaded, stowed and secured with respect to the CSS code. CSS code provides guidance on appropriate stowage and securing of cargo and should be utilised as the basis for the CSM. The CSM that is specifically tailored to the ship identifies the containers stowage and lashing equipment in detail.

Containership cargo operation requires efficient teamwork to carry out rapid, safe and systematic loading and discharging. All deck team knowledge must be competent for proper stowage and handling of the cargo onboard the ship. Deck Officers, able seamen and deck cadet must be familiar with cargo plan to monitor the operation and containers including their specific markings and dimensions to determine their stowed position. It is also rather important to well understand the Bay-Plan that helps in the ready identification of containers. The correct stowage positions of containers are determined in the bay-plan as per the stowage plan. A bay plan is a system that consists of numerical coordinates relating to bay, row and tier of containers on a vessel above and below the deck as depicted in Figure 4.2, below.

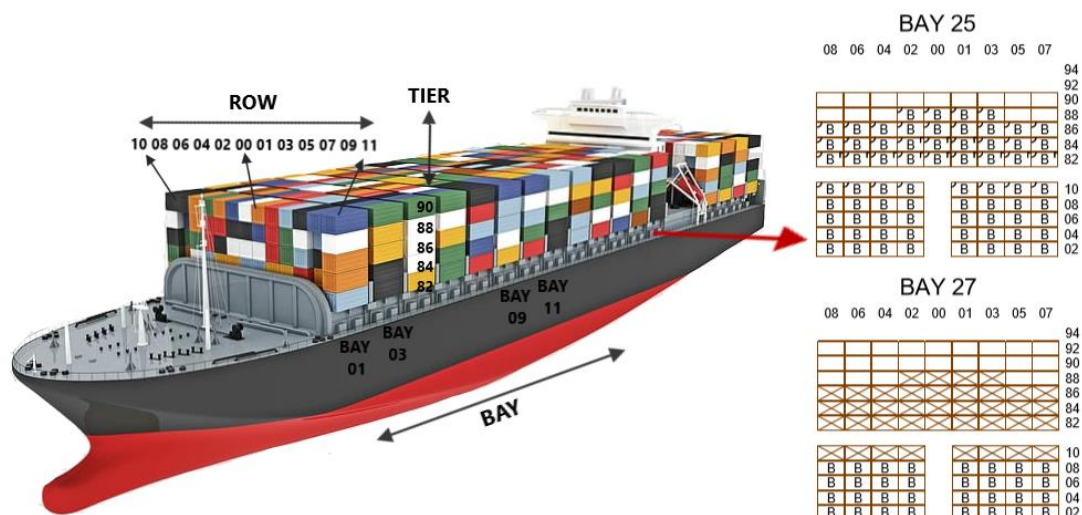


Figure 4.2 : Visual description of a containership.

It comprises 6 digits and the first two of six digits represent the bay, the next two digits represent the row and the final two digits represent the tier on the plan. The stowed position of some special containers must be checked strictly by Deck Officer, able seamen and cadet who are responsible for monitoring the loading/discharging during operation.

The Chief Officer is responsible for safe and secure handling and the stack of the containers throughout the port time. First of all, the Chief Officer controls the provisional plans which are sent to the ship before arrival in port in accordance with stress values such as bending moment, shear force and torsion force, calculating the ship's stability as well as verifying stack weight limitations. And then, the prepared plan is distributed to the deck team to check the correctness of the stowed positions of containers.

The stowage plan is the primary item that needs to be checked properly during any step of the cargo operation. To ensure that the loading and discharging of containers are carried out in accordance with the prepared plans is the responsibility of the duty officer. Any container not complying with the plan shall be immediately present to the attention of the Chief Officer and the authorized person who is called as Planner. He/she also monitors the tank condition and carry out the heeling operation if necessary to maintain the stability of the ship at all times. Accordingly, the Chief Officer is authorized person to warn about loading containers in balance onto port and starboard side of the ship. In case ship heels precariously (more than 5 degrees, i.e),

the operation shall be stopped by him/her immediately and the charterer/agent shall be informed. Terminals are to inform the planning office and the responsible crew without delay in case the weight distribution of the container stowage is altered significantly.

The Deck Officer is mainly responsible for safe cargo handling and stacking throughout the port time. During the watch, he/she monitor the stowed positions of any cargo as per the bay plan. The deck officer is aware of the operational risks and as a deck team leader, informs the Chief Officer at every stage of cargo operation. A competent deck officer has extensive knowledge of the safety of the cargo, ship and crew. He/She represent the Chief Officer in the deck to third persons (foreman, stevedore...etc) and provide information flow between them.

The ship's draft is the other crucial item to be regularly checked and recorded during and after the cargo operation. A duty officer shall make a visual check to inform the Chief Officer properly. The obtained drafts also shall be compared with the expected drafts according to the loadmaster programme in terms of they match each other or not.

Specific containers such as IMDG, OH/OG and reefers demands great attention and care when loading on board. Their stowed position shall be exactly matched with bayplan. IMDG containers shall be stacked as per the document of compliance with the special requirements for ships carrying dangerous goods. IMO Class and HAZMAT labels shall be present on all visible sides of the IMDG containers.

The types of dangerous goods are classified under nine groups as follows: Group I: Explosive Materials, Group II: Gaseous Materials, Group III: Inflammable Liquids, Group IV: Inflammable Solids or Substances, Group V: Materials containing peroxides, easily oxidising contents, Group VI: Substances highly toxic and infective, Group VII: Radioactive substances and materials, Group VIII: Erosive Materials, Group IX: Dangerous materials and substances miscellaneous in nature. The classification of dangerous goods is stated in the IMDG Code which is subjected to SOLAS 74 and MARPOL 73/78 convention of the IMO.

Reefers are the other sensitive cargoes requiring more care and proper check. The electrician is responsible for the maintenance of reefer containers on board. The stowed reefers shall be cautiously plugged in and connected immediately. The setpoints value (temperature degree, ventilation and humidity settings) electrical

connections, water hose connections shall be cross-checked with reference to the reefer manifest and noted on the reefer form. Faulty reefers shall be rejected from being stowed onboard.

Lashings of stacked containers need to be regularly checked throughout the lashing operations. The lashing plan prepared in accordance with CSM should fit the cargo properly. The deck team, coordinated by the chief officer, is responsible for the correct execution thereof. Securing containers carrying on deck is based on locking containers on deck fittings, interconnecting containers with twist locks, and a lashing bar system. Therefore, the lashing equipment shall be durable and properly maintained. The containers shall be equipped with adequate and proper twist locks especially upper lines on deck. The containers in the first tier are positioned on fixed twist-lock foundations on top of the hatch covers. The containers in the next tiers are stacked one on top of the other, connected with twist locks. Although it varies per vessel, lashing bars are fitted up to the third tier. These bars are put diagonally so that the relevant container and the lashings work together to resist racking. At this point, no stack is connected with another to keep cargo handling flexible. As for the stacked containers in the hold, they are secure with vertical cell guides.

Hatch cover cleats shall be checked before and after hatch cover operation. Stevedores or able seamen performs the lashing and de-lashing, this may vary per vessel or port. Foreman is the contact person to be notified onboard in case any missing or damaged lashing equipment and twist locks are determined. The lashings of out of gauge (OOG) and over high (OH) cargoes shall be cross-checked with the foreman and planner as well as the Chief Officer before being stowed onboard. As lashing gearboxes are handled by shore stevedores, a proper check is needed once the cargo operation is all completed.

For safe stability, bending moment, torsion moment, shearing force and trim shall be calculated and considered at any time as well as GM values and the ship shall never be overload. The CSS code states that through supervision of the loading operations improper stowage should be prevented onboard ships. Unless required otherwise, empty containers shall be stowed on top of heavy ones. Similarly, light containers are stowed on top to increase GM value which is the distance between the centre of gravity of the ship and its metacentre in case of low GM value.

In general, the GM values of containerships are high, and as the GM increases, the rolling periods of the ship decrease. However, this situation shall increase the stresses on the lashing. After loading is completed, the departure plan is obtained from the terminal and loaded in digital format into the computer in the cargo office on board. The container data are automatically loaded into the computer through standard EDIFACT (.edi) files.

The visibility line and/or steering light is the vulnerable point for the safe navigation of Containerships. Visibility from the conning position of the bridge shall comply with IMO visibility requirements. SOLAS, 1974 defines the visibility requirements in detail in Chapter V (Reg. 22). Therefore, the IMO visibility line shall be considered when planning the stowage of containers especially on upper lines on deck. Any stage and latest status of cargo operation shall be noted to the port logbook and ship's journal from time to time. Further, the required checklist shall be completed properly.

4.4.2 Hierarchial task analysis

Cargo operations become even more important today due to the marine environment and eco-system faces a considerable amount of problems. Containership operations are one of the most complex environments within the transport industry. Coping with increasing container handling capacities, the ships and terminals come under pressure to keep operational safety and this situation causes a heavy workload. Since one of the main goals of this thesis is to systematically predict human error probability for designated tasks and to enhance operational safety onboard containerships, the real shipboard loading operation is handled in the illustrative process. The operational system is mainly divided into five processes; pre-arrival, before loading, during loading, after loading and pre-departure. In this context, Table 4.4 provides the HTA for the operational processes onboard containership. Accordingly, the daily loading operations involved in a container terminal are included in detail. In light of the table, the "pre-arrival" process of loading operation consists of sub-tasks 1.1 to 1.5. The "before-loading" process consists of sub-tasks 2.1 to 2.6. The "during loading" process is covered in two different topics; human safety that consists of sub-tasks 3.1.1 to 3.1.5, and ship/cargo security that consists of 3.2.1 to 3.2.19. As for the "after loading" process, it consists of sub-tasks 4.1 to 4.9. The last process of the containership loading operation is the "pre-departure" process and consist of sub-tasks 5.1 to 5.8.

Table 4.4 : Hierarchial task analysis.

Process	Task	Task Description
1.	1.1	Prepare stowage and bay plan
	1.2	Consider Max. Tier stack weight value as well as max stack weight while preparing stowage plan
	1.3	Check the provisional list of dangerous goods
	1.4	Check if the stowage plan is in accordance with the requirements of the IMDG Code
	1.5	Check if the stowage plan is proper to follow the reefer container process flowchart
2.	2.1	Check if the accommodation ladder is free from the crane path at the pier
	2.2	Make sure that the auto-heeling pump is actively running before cargo operation
	2.3	Make sure that all lashing equipment (twist lock, cone, bar) are qualified and ready for use
	2.4	Check if any equipment is on the hatch cover before the operation
	2.5	Be ensure if the hatch covers are not damaged on the shoreside
	2.6	Check if any equipment is in the hold bottom
3.1	3.1.1	Make sure that all crew on deck use PPE
	3.1.2	Use a safety belt when working/climbing on containers
	3.1.3	Keep clear from the container passage area
	3.1.4	Be aware of the risks of mislaid equipment on the operated container
	3.1.5	Be aware of the risks of lashing operations on bays at which cargo operations continue
3.2	3.2.1	Check if any oil is dropped off from the gantry to the deck
	3.2.2	Check all cell guides against any damage during operation
	3.2.3	Check the seal of loading containers
	3.2.4	Check if the top cover of the OT container is damaged and not prevent another container which put on them.
	3.2.5	Check the IMO signs/labels of dangerous cargoes
	3.2.6	Check the tightness of all straps on flat rack containers if any
	3.2.7	Make sure that the on/off switch is kept off before connecting of reefer plug
	3.2.8	Check the temperature setting degree and ventilation and humidity settings (%) of the reefer container
	3.2.9	Consider the height while loading HC/OT containers in the hold
	3.2.10	Inform C/O in case the flatrack container is overhighed or overgauged than declared
	3.2.11	Check if loading containers in balance on to port/starboard side of the ship
	3.2.12	Inform the office-charterer-agent if the ship heels more than 5 degrees during loading
	3.2.13	Inform C/O if hook spreaders are used for cargo operations
	3.2.14	Check if the leakage containers on board
	3.2.15	Inform C/O in case damaged container is observed
	3.2.16	Prepare interchange report for damaged containers
	3.2.17	Inform the charterer and management office if the container is heavily damaged

Table 4.4 (continued) : Hierarchial task analysis.

Process	Task	Task Description
3.2	3.2.18	Check the ship's ropes during the operation frequently
	3.2.19	Keep the drafts under strict control during cargo operation
4.	4.1	Check if the visibility line and/or steering light is blocked
	4.2	Confirm that all containers are loaded in accordance with planned stow.
	4.3	Check the final setpoint value of reefer containers and kept the records in file
	4.4	Make sure that there are no lashing gears randomly thrown on deck
	4.5	Inspect that all lashing equipment are exact/not missing
	4.6	Check and confirm the position of the gearboxes visually
	4.7	Make sure that all twist locks are in the locked position
	4.8	Check if the cleats on all sides of all hatch covers are locked
	4.9	Check if the lashing operation is carried out in compliance with Cargo Securing Manuel
5.	5.1	Record the final drafts on port log book
	5.2	Make sure that auto-heeling pump is properly deactivated
	5.3	Make sure that the GM value complies with the limit of the minimum required GM value that given by loadmaster +40 cm limit
	5.4	Check if sea condition %95 stress is exceeded
	5.5	Make sure that stress values are calculated and signed
	5.6	Ensure that final lists/documentation and certificates of goods actually loaded are provided
	5.7	Check if the ship and shore cranes are clear
	5.8	Check the ship's and gantry's air drafts

4.5 Selection Criteria and Analysis of Marine Experts

The SLIM approach employs the experts' judgements in the decision-making process. Expert judgements can penetrate further than any set of data when it comes to enunciating the significance of PSFs (Kirwan, 1994). The judgements of experts are quite required to rate the PSF on related tasks and weigh them according to their perceived contribution in the process. It is practical and alternative in the HEP prediction due to the lack of data in maritime transportation. In this regard, the core and crucial step is the formation of a committee of experts to generate the relevant data reliably (Khan et al, 2006).

The experts should have extensive knowledge and background on maritime transportation especially experience in cargo operations onboard containership. Based on this, the following criteria were determined to form an expert committee:

- Minimum Oceangoing Master capacity.

- Minimum 10 years of experience onboard containership.
- Actively being participated in loading operation onboard containership.
- Having the required time to perform assessments.
- Available to meet in person during data collection.

Accordingly, the profiles of the committee consisting of ten members are demonstrated in Table 4.5.

Table 4.5 : Marine experts' profile details.

Expert ID	Age	Company	Position	Experience (yrs)
1	43	A	Operation Manager	14
2	48	B	Oceangoing Master	15
3	43	C	Oceangoing Master	10
4	41	B	Oceangoing Master	18
5	44	B	Oceangoing Master	13
6	64	C	Oceangoing Master	25
7	43	C	Oceangoing Master	22
8	36	D	CFS Operation Manager	10
9	35	C	Oceangoing Master	11
10	40	C	Oceangoing Master	16

4.6 Definition of Operation

In order to demonstrate the proposed IT2FS-SLIM approach, a real-shipboard cargo operation has been monitored in the prestigious and reliable container shipping company. The vessel of the shipping company is instructed to berth to Lisbon port after stayed 10 hours at Lisbon anchorage area on May 1, 2020. The pilot embarked to the vessel at 07:00 am, the vessel berth was clear and starboard side alongside. After all fast at 08:10 am, the ISPS equipment check has been carried out.

The operation commenced with the handling of lashing gearboxes by shore stevedores at 08:15 am on May 2, 2020. The wind force was 2 (around 9 knots/hour) as SW directional and the sea state was smooth. The sky observed as cloudy, the visibility was clear and the air temperature was 19 degrees (dry thermometer). To sum up, there was not any environmental obstacle hindering cargo operation. Additionally, bunker operation has not been carried throughout the port time.

Discharging operation commenced at 08:20 am from Bay 43-45 with one gang and continued from Bay 01-03, Bay 29-31, respectively. Discharging operation was all completed at 03:10 pm. Loading operation commenced at Bay 01-03 at 03:15 pm

following the completion of discharge operation. Operation ceased approximately 2 hours due to spreader failure till 05:05 pm and then the number of the gang was increased to 2 to continue loading operation. As for specific containers that need more attention and meticulous check, 8 dangerous cargoes with different IMDG classes (3 units are class 5.1, 2 units are class 3, 1 unit is class 8 and 2 units are class 9) were loaded and reached 27 in total on board. 16 reefer containers were loaded and plugged cautiously by the Electrician. Similarly, 4 OOG containers were stowed and lashed gingerly. The loading operation was completed with the close of hatch cover of bay 39-41 at 11:15 am and all finish time was recorded at 11:20 am on May, 3. The number and type of containers stowed on the vessel at Lisbon Port according to the ports to be discharged are given in Figure A.1 in detail. The loading process was carried out by participation of the deck crew (second officer, third officer, bosun, able seaman, electrician for reefers, and deck cadet) coordinated by the Chief Officer.

4.7 PSF Derivation

PSFs are of direct correlation with human performance (Islam et al, 2016). However, the most prevalent PSFs should be determined in affecting the tasks as opposed to eliciting all the possible shaping factors. Seven PSF were adopted in this study as given in Table 4.6 for loading operation onboard containership.

Table 4.6 : Determined PSFs for loading operation.

PSFs	
External Factors	Internal Factors
Stress	Experience
Limited Time	Training
Complexity	Fatigue
Safety Culture	

Five of them have been determined by the elicitation review team (ERT) consisting of twenty-four members. Their primary job functions were: engineering (fourteen members), health and safety (three members), operations (six members) and administrative (one member) (Akyuz, 2016; DiMattia et al, 2005). The rest of the PSFs are fatigue and safety culture. Fatigue is of utmost importance on crew performance as the nature of work mostly requires physical activities especially during cargo operation at the port. Similarly, as the global standard-setting authority for the safety, IMO, emphasizes the importance of an effective safety culture in preventing

occupational accidents for the shipping industry (Solmaz et al, 2020). A brief description of each PSF included in the HEP assessment is given below, respectively.

- *Stress*: Negative effect upon seafarer performance to complete the task properly due to increase anxiety and pressure.
- *Experience*: Familiarity with the task and knowledge.
- *Training*: Expansion of knowledge, performance and capability of seafarers by activities or actions organized by ship management.
- *Fatigue*: Extreme tiredness caused by mental/physical workload or illness.
- *Limited Time*: Amount of time required for the seafarer to complete the relevant task.
- *Complexity*: Measure of task difficulty that identifies interrelated and interdependent task components.
- *Safety Culture*: Both individual or group perceptions, attitudes and values that reflect ship management's commitment to safety.

4.8 PSF Rating

Rating is the crucial part of calculating SLI in the SLIM process (Islam et al, 2017). To enhance consistency, the rating is assigned for each of the seven selected PSFs and 52 sub-tasks of containership loading operation. The values are between 1 and 9 on a linear scale. In essence, marine experts are asked to assign to each task a rating, between the two endpoints that accurately reflects their judgements. The calculated geometric means of each PSF based on the marine experts' assignments are provided in Table 4.7.

4.9 PSF Weighting

Because the PSFs are not all of equal importance in the loading operation process, weightings of them are obtained. By determining where the experts' judgement is changed, the weighting of the effect of each PSF on the task success is inferred. To enhance the accuracy of the outcome, this process is carried out on the basis of the interval type-2 fuzzy linguistic scale developed by Lee and Chen (2008). Table 4.8 illustrates the trapezoidal fuzzy numbers (IT2FSs numbers) and upper and lower membership functions related to the linguistic assessments.

Table 4.7 : Geometric means of PSF ratings based on the experts' evaluations.

Sub-Task	Performance Shaping Factor						Safety Culture
	Stress	Experience	Training	Fatigue	Time L.	Complexity	
1.							
1.1	4	3	4	3	3	4	4
1.2	4	3	3	3	3	4	4
1.3	3	3	3	3	3	3	3
1.4	3	3	3	3	3	3	3
1.5	3	3	4	3	4	4	3
2.							
2.1	4	4	5	4	4	5	3
2.2	3	3	4	3	3	3	3
2.3	5	4	4	3	3	4	3
2.4	5	4	4	3	4	4	3
2.5	5	3	4	3	3	4	3
2.6	5	4	4	4	4	5	4
3.1							
3.1.1	5	3	3	3	3	3	2
3.1.2	4	3	3	3	3	3	2
3.1.3	4	3	4	3	4	3	2
3.1.4	4	3	3	3	3	3	2
3.1.5	4	3	3	3	3	3	2
3.2							
3.2.1	4	3	4	3	3	4	3
3.2.2	5	3	4	4	3	4	3
3.2.3	5	3	4	3	3	4	3
3.2.4	4	3	4	3	3	4	3
3.2.5	5	3	4	3	3	4	3
3.2.6	5	3	3	3	3	4	3
3.2.7	5	3	4	3	3	4	2
3.2.8	5	3	4	3	3	4	3
3.2.9	4	3	4	3	3	3	3
3.2.10	5	3	4	3	3	4	2
3.2.11	4	3	4	3	3	4	2
3.2.12	4	3	3	3	3	4	2
3.2.13	4	3	3	3	3	3	2
3.2.14	4	2	3	3	3	4	2
3.2.15	4	3	3	3	3	4	2
3.2.16	4	3	3	3	4	4	3
3.2.17	3	2	3	3	3	4	2
3.2.18	5	3	4	3	3	4	2
3.2.19	4	3	3	3	3	4	3
4.							
4.1	4	3	3	3	3	3	2
4.2	4	3	3	3	3	3	2
4.3	4	3	4	3	3	4	2
4.4	4	3	4	3	3	4	2
4.5	3	3	4	3	2	4	2
4.6	4	3	4	3	3	4	3
4.7	4	3	4	3	2	4	2
4.8	4	3	3	2	3	4	2
4.9	4	3	3	3	3	3	2

Table 4.7 (continued) : Geometric means of PSF ratings based on the experts' evaluations.

Sub-Task	Performance Shaping Factor						Safety Culture
	Stress	Experience	Training	Fatigue	Time L.	Complexity	
5.							
5.1	4	4	4	3	4	4	3
5.2	3	3	3	2	3	3	2
5.3	3	2	3	3	3	3	2
5.4	3	2	3	3	3	3	2
5.5	4	3	3	3	3	3	2
5.6	4	3	3	3	3	3	2
5.7	4	3	4	3	3	4	2
5.8	4	3	3	3	3	3	2

Table 4.8 : Linguistic terms and their corresponding IT2FSs.

Linguistic Assessment	Term	Interval Type-2 Fuzzy Sets
Very Low	VL	$((0.0;0.0;0.0;0.1;1.0;1.0) , (0.0;0.0;0.0;0.05;0.9;0.9))$
Low	L	$((0.0;0.1;0.1;0.3;1.0;1.0) , (0.05;0.1;0.1;0.2;0.9;0.9))$
Medium Low	ML	$((0.1;0.3;0.3;0.5;1.0;1.0) , (0.2;0.3;0.3;0.4;0.9;0.9))$
Medium	M	$((0.3;0.5;0.5;0.7;1.0;1.0) , (0.4;0.5;0.5;0.6;0.9;0.9))$
Medium High	MH	$((0.5;0.7;0.7;0.9;1.0;1.0) , (0.6;0.7;0.7;0.8;0.9;0.9))$
High	H	$((0.7;0.9;0.9;1.0;1.0;1.0) , (0.8;0.9;0.9;0.95;0.9;0.9))$
Very High	VH	$((0.9;1.0;1.0;1.0;1.0;1.0) , (0.95;1.0;1.0;1.0;0.9;0.9))$

In the light of the above, the marine experts assess the relative importance of each PSF in comparison to the PSF judged to be the most important with that linguistic terms. Each weight being assigned by marine experts is provided in Table 4.9 below.

Table 4.9 : Linguistic evaluations of marine experts for each PSF.

PSF	Exp.1	Exp.2	Exp.3	Exp.4	Exp.5	Exp.6	Exp.7	Exp.8	Exp.9	Exp.10
Stress	ML	MH	M	VH	MH	ML	M	MH	M	ML
Experience	VH	H	H	H	H	MH	VH	H	VH	VH
Training	H	ML	MH	M	M	M	MH	M	H	MH
Fatigue	H	H	H	VH	VH	MH	H	VH	H	VH
Time Lim.	VH	VH	VH	H	H	H	H	M	MH	VH
Complexity	MH	M	MH	MH	ML	M	MH	ML	H	M
Safety Cul.	H	H	VH	VH	H	VH	VH	H	VH	VH

Accordingly, marine experts' linguistic variables are converted to the interval type-2 fuzzy sets by utilizing a set of mathematical operations denoted in equations (3.4), (3.5), (3.6), (3.7), and (3.8) to transform all judgements into one judgement. Right after having calculated average IT2FS values, defuzzified IT2FS values are obtained based on equation (3.3). Table 4.10 illustrates the IT2FSs together with the crisp and normalised values of each PSF.

Table 4.10 : Calculated average IT2F values.

PSF	Interval Type-2 Fuzzy Sets	Crisp Value	Normalised Value
Stress	((0.36;0.55;0.55;0.73;1;1), (0.46;0.55;0.55;0.64;0.9;0.9))	0.604	0.107
Experience	((0.76;0.92;0.92;0.99;1;1) , (0.84;0.92;0.92;0.96;0.9;0.9))	0.929	0.165
Training	((0.42;0.62;0.62;0.8;1;1) , (0.52;0.62;0.62;0.71;0.9;0.9))	0.673	0.119
Fatigue	((0.76;0.92;0.92;0.99;1;1) , (0.84;0.92;0.92;0.96;0.9;0.9))	0.929	0.165
Time Lim.	((0.72;0.88;0.88;0.96;1;1) , (0.8;0.88;0.88;0.92;0.9;0.9))	0.893	0.158
Complexity	((0.38;0.58;0.58;0.77;1;1) , (0.48;0.58;0.58;0.68;0.9;0.9))	0.637	0.114
Safety Cul.	((0.82;0.96;0.96;1;1;1) , (0.89;0.96;0.96;0.98;0.9;0.9))	0.957	0.171
		5.62	1.00

Safety culture (0.171), experience (0.165), fatigue (0.165) and time limitation (0.158) were found to be the critical PSFs that highly influencing crew performance during the loading operation process, respectively.

4.10 Determination of SLI

The success likelihood index represents the non-occurrence likelihood of the target human error in the SLIM approach. The SLI values for each sub-tasks are calculated based on equation (3.1) given in chapter 3 in detail. Accordingly, the SLI of each sub-tasks of the loading operation process is illustrated below, respectively. Table 4.11 illustrates the calculated SLIs for the "pre-arrival" process (sub-tasks 1.1 to 1.5) of loading operation onboard container ship. Following this process, Table 4.12 illustrates the calculated SLIs for the "before loading" process (sub-tasks 2.1 to 2.6) of loading operation. As mentioned above, the "during loading" process is handled in two different topics consisting of human safety and ship/cargo security. Calculated SLIs for sub-tasks 3.1.1 to 3.1.5 and sub-tasks 3.2.1 to 3.2.19 are provided in Table 4.13. Right after, Table 4.14, illustrates the calculated SLIs for the "after-loading" process consists sub-tasks 4.1 to 4.9 of loading operation. Finally, SLIs for the last process (sub-tasks 5.1 to 5.8) of the loading operation are as illustrated in Table 4.15.

Table 4.11 : SLI values for "pre-arrival" process.

Sub-Task	Task Description	SLI
1.1	Prepare stowage and bay plan	3.38
1.2	Consider Max. Tier stack weight value as well as max stack weight while preparing stowage plan	3.37
1.3	Check the provisional list of dangerous goods	3.15
1.4	Check if the stowage plan is in accordance with the requirements of the IMDG Code	3.18
1.5	Check if the stowage plan is proper to follow the reefer container process flowchart	3.30

Table 4.12 : SLI values for "before loading" process.

Sub-Task	Task Description	SLI
2.1	Check if the accommodation ladder is free from the crane path at the pier	4.07
2.2	Make sure that the auto-heeling pump is actively running before cargo operation	2.96
2.3	Make sure that all lashing equipment (twist lock, cone, bar) are qualified and ready for use	3.76
2.4	Check if any equipment is on the hatch cover before the operation	3.68
2.5	Be ensure if the hatch covers are not damaged on the shoreside	3.63
2.6	Check if any equipment is in the hold bottom	4.05

Table 4.13 : SLI values for "during loading" process.

Sub-Task	Task Description	SLI
3.1		
3.1.1	Make sure that all crew on deck use PPE	3.10
3.1.2	Use a safety belt when working/climbing on containers	3.01
3.1.3	Keep clear from the container passage area	3.30
3.1.4	Be aware of the risks of mislaid equipment on the operated container	3.08
3.1.5	Be aware of the risks of lashing operations on bays at which cargo operations continue	2.79
3.2		
3.2.1	Check if any oil is dropped off from the gantry to the deck	3.47
3.2.2	Check all cell guides against any damage during operation	3.57
3.2.3	Check the seal of loading containers	3.51
3.2.4	Check if the top cover of the OT container is damaged and not prevent another container which put on them.	3.40
3.2.5	Check the IMO signs/labels of dangerous cargoes	3.41
3.2.6	Check the tightness of all straps on flat rack containers if any	3.12
3.2.7	Make sure that the on/off switch is kept off before connecting of reefer plug	3.21
3.2.8	Check the temperature setting degree and ventilation and humidity settings (%) of the reefer container	3.25
3.2.9	Consider the height while loading HC/OT containers in the hold	3.19
3.2.10	Inform C/O in case the flatrack container is overhighed or overgauged than declared	3.30
3.2.11	Check if loading containers in balance on to port/starboard side of the ship	3.33
3.2.12	Inform the office-charterer-agent if the ship heels more than 5 degrees during loading	3.20
3.2.13	Inform C/O if hook spreaders are used for cargo operations	3.04
3.2.14	Check if the leakage containers on board	2.87
3.2.15	Inform C/O in case damaged container is observed	3.02
3.2.16	Prepare interchange report for damaged containers	3.29
3.2.17	Inform the charterer and management office if the container is heavily damaged	2.94
3.2.18	Check the ship's ropes during the operation frequently	3.27
3.2.19	Keep the drafts under strict control during cargo operation	3.30

Table 4.14 : SLI values for "after loading" process.

Sub-Task	Task Description	SLI
4.1	Check if the visibility line and/or steering light is blocked	3.04
4.2	Confirm that all containers are loaded in accordance with planned stow.	2.89
4.3	Check the final setpoint value of reefer containers and kept the records in file	3.09
4.4	Make sure that there are no lashing gears randomly thrown on deck	3.08
4.5	Inspect that all lashing equipment are exact/not missing	2.87
4.6	Check and confirm the position of the gearboxes visually	3.22
4.7	Make sure that all twist locks are in the locked position	2.95
4.8	Check if the cleats on all sides of all hatch covers are locked	2.86
4.9	Check if the lashing operation is carried out in compliance with Cargo Securing Manuel	2.80

Table 4.15 : SLI values for "pre-departure" process.

Sub-Task	Task Description	SLI
5.1	Record the final drafts on port log book	3.69
5.2	Make sure that auto-heeling pump is properly deactivated	2.76
5.3	Make sure that the GM value complies with the limit of the minimum required GM value that given by loadmaster +40 cm limit	2.74
5.4	Check if sea condition %95 stress is exceeded	2.75
5.5	Make sure that stress values are calculated and signed	2.81
5.6	Ensure that final lists/documentation and certificates of goods actually loaded are provided	2.95
5.7	Check if the ship and shore cranes are clear	3.14
5.8	Check the ship's and gantry's air drafts	3.01

In this case, sub-task 3.1.5 (Be aware of the risks of lashing operations on bays at which cargo operations continue), sub-task 3.2.14 (Check if the leakage containers onboard), sub-task 4.2 (Confirm that all containers are loaded in accordance with planned stow), sub-task 4.5 (Inspect that all lashing equipment are exact/not missing), sub-task 4.8 (Check if the cleats on all sides of all hatch covers are locked), sub-task 4.9 (Check if the lashing operation is carried out in compliance with Cargo Securing Manuel), sub-task 5.2 (Make sure that auto-heeling pump is properly deactivated), sub-task 5.3 (Make sure that GM value complies with the limit of the minimum required GM value that given by loadmaster +40 cm limit), sub-task 5.4 (Check if sea condition %95 stress is exceeded) and sub-task 5.5 (Make sure that stress values are calculated and signed) stands out amongst others by having the lowest SLI, specifically. At this point, the higher SLI is the value describing the lower occurrence of human error probability. Accordingly, the determined SLIs are transformed into HEPs in the next step of the SLIM approach.

4.11 HEP Calculation

In order to obtain HEP values for each subtask, it is necessary to convert SLI values into the corresponding absolute probability values. The calibration equation (3.2) of SLIM that includes a logarithmic relationship is utilized to convert SLIs into HEPs for this step. A sensitive HEP calculation is performed to quantify HE for each subtask of the containership loading operation.

In accordance with the sensitive calculation carried out, Table 4.16 illustrates the detailed results of HEP calculations for the "pre-arrival" process (sub-tasks 1.1 to 1.5), Table 4.17 illustrates the results of HEP calculations for the "before loading" process (sub-tasks 2.1 to 2.6), Table 4.18 illustrates the results of HEP calculations for the "during loading" process (sub-tasks 3.1.1 to 3.1.5 and sub-tasks 3.2.1 to 3.2.19), Table 4.19, illustrates the results of HEP calculations for the "after loading" process (sub-tasks 4.1 to 4.9) and finally, Table 4.20 illustrates the results of HEP calculations for the "pre-departure" process (sub-tasks 5.1 to 5.8) of the containership loading operation, respectively.

The obtained HEP values utilizing in the data derivation for risk determination are discussed extensively in the next chapter.

Table 4.16 : Calculated HEP values for "pre-arrival" process.

Sub-Task	SLI	<i>Log-HEP</i>	Constant <i>a</i>	Constant <i>b</i>	HEP
1.			-2.8	7.1	
1.1	3.38	-2.38			4.20E-03
1.2	3.37	-2.33			4.63E-03
1.3	3.15	-1.71			1.95E-02
1.4	3.18	-1.80			1.59E-02
1.5	3.30	-2.13			7.35E-03

Table 4.17 : Calculated HEP values for "before loading" process.

Sub-Task	SLI	<i>Log-HEP</i>	Constant <i>a</i>	Constant <i>b</i>	HEP
2.			-2.8	7.1	
2.1	4.07	-4.28			5.22E-05
2.2	2.96	-1.19			6.45E-02
2.3	3.76	-3.43			3.70E-04
2.4	3.68	-3.21			6.13E-04
2.5	3.63	-3.07			8.50E-04
2.6	4.05	-4.23			5.82E-05

Table 4.18 : Calculated HEP values for "during loading" process.

Sub-Task	SLI	<i>Log-HEP</i>	Constant <i>a</i>	Constant <i>b</i>	HEP
3.1			-2.8	7.1	
3.1.1	3.10	-1.59			2.59E-02
3.1.2	3.01	-1.31			4.85E-02
3.1.3	3.30	-2.13			7.33E-03
3.1.4	3.08	-1.54			2.90E-02
3.1.5	2.79	-0.72			1.91E-01
3.2					
3.2.1	3.47	-2.61			2.46E-03
3.2.2	3.57	-2.89			1.29E-03
3.2.3	3.51	-2.73			1.88E-03
3.2.4	3.40	-2.42			3.82E-03
3.2.5	3.41	-2.45			3.58E-03
3.2.6	3.12	-1.65			2.25E-02
3.2.7	3.21	-1.89			1.28E-02
3.2.8	3.25	-2.00			9.90E-03
3.2.9	3.19	-1.83			1.47E-02
3.2.10	3.30	-2.14			7.30E-03
3.2.11	3.33	-2.23			5.94E-03
3.2.12	3.20	-1.86			1.37E-02
3.2.13	3.04	-1.40			3.95E-02
3.2.14	2.87	-0.94			1.14E-01
3.2.15	3.02	-1.35			4.43E-02
3.2.16	3.29	-2.12			7.62E-03
3.2.17	2.94	-1.13			7.45E-02
3.2.18	3.27	-2.05			8.84E-03
3.2.19	3.30	-2.15			7.05E-03

Table 4.19 : Calculated HEP values for "after loading" process.

Sub-Task	SLI	<i>Log-HEP</i>	Constant <i>a</i>	Constant <i>b</i>	HEP
4.			-2.8	7.1	
4.1	3.04	-1.43			3.76E-02
4.2	2.89	-0.99			1.03E-01
4.3	3.09	-1.55			2.81E-02
4.4	3.08	-1.53			2.95E-02
4.5	2.87	-0.95			1.13E-01
4.6	3.22	-1.91			1.22E-02
4.7	2.95	-1.17			6.72E-02
4.8	2.86	-0.92			1.20E-01
4.9	2.80	-0.74			1.81E-01

Table 4.20 : Calculated HEP values for "pre-departure" process.

Sub-Task	SLI	Log-HEP	Constant <i>a</i>	Constant <i>b</i>	HEP
5.			-2.8	7.1	
5.1	3.69	-3.23			5.94E-04
5.2	2.76	-0.62			2.41E-01
5.3	2.74	-0.58			2.64E-01
5.4	2.75	-0.60			2.50E-01
5.5	2.81	-0.77			1.71E-01
5.6	2.95	-1.17			6.83E-02
5.7	3.14	-1.69			2.06E-02
5.8	3.01	-1.33			4.66E-02

A basic sample calculation of HEP for Sub-task 3.1.1 (Make sure that all crew on deck use PPE) is also presented in Table 4.21 to illustrate how to calculate the HEP results by using the proposed model in more detail.

Table 4.21 : A basic sample of calculation for the HEP.

Normalised Values (<i>w</i>)		Geometric means of Experts' PSF Ratings (<i>r</i>) for Sub-Task 3.1.1						
<i>Stress</i>	0.107	<i>Stress</i>	Exp.	Training	Fatigue	Time Lim.	Complexity	Safety C.
Experience	0.165	5	3	3	3	3	3	2
Training	0.119	$SLI = \sum_{i=1}^n r_i w_i$						
Fatigue	0.165							
Time Lim.	0.158							
Complexity	0.114							
Safety Cul.	0.171	$SLI = 3.10$						
HEP	$Log (HEP) = aSLI + b$							
Calculation for Sub- Task 3.1.1.	<i>a</i> −2.8	<i>b</i> 7.1	$Log (HEP) = −1.59$			HEP for Sub-Task 3.1.1 = 2.59E − 02		

Operational reliability is mainly related to human performance in performing the assigned tasks. In this context, all process including sub-tasks should be completed properly to perform a safe operation at the desired level. In case any process fails, the entire loading operation will fail. At this point, determining the human error-related risks which are the potential causes for losses will be a step in the right direction to minimise future losses. Accordingly, a comprehensive risk analysis is carried out in the next chapter to check whether the loading operation is safe.

5. HUMAN ERROR CONTRIBUTION TO RISK DETERMINATION

As the last step of the hybrid approach, a comprehensive risk analysis is carried out for the purpose of demonstrating the capability of evaluating the potential human error contributions to the operational risks.

5.1 A Quantitative Risk Analysis for Container Loss

Risk analysis enables the study to illustrate how human error contributes to risk in maritime transportation. Based on this, the risk of container loss throughout the cargo operation is investigated since container losses can lead to severe damage and catastrophic events in a terminal. To achieve this, FTA is combined under the interval type-2 fuzzy logic based SLIM.

5.2 Problem Statement

As a result of several container losses in containership incidents especially occurred over the last two decades, the maritime industry has taken the issue of operational safety very seriously. Various investigations of potential risks with cargo operations involving human-related activities have been conducted to avoid future losses. At this point, some of the current factors triggering container losses should be determined to clarify what measures may be necessary to improve the safety and efficiency of container transportation. Many factors ranging from environmental conditions to more catastrophic events such as explosion, collision, grounding can result in containers being lost at sea. On the other hand, the probability of having other serious marine events such as capsizing, listing, structural fracture, and stack collapse causing container loss is also crucial during the cargo handling operations at the port period.

Onboard a container ship, a loss of a container leads to many issues. For instance, the containers around shall most likely be damaged or containers shall be lifted causing damage to the lashings. The improperly stacked/lashed container cause a lateral force on the others. This container pushes against the container in the next row or pulls

towards itself. Namely, the mobility of any container has the effect of exerting direct force from one to another such as the domino effect. One loss leads to part of other stacked containers falling over, collapse or broken lashing for a container ship. Accordingly, the main goal of a safe stack and securing cargo is to absorb forces.

The loss of a container not only results in severe damage to a ship's safety and cargo, but also the crew onboard, shore-based workers, port facilities, and the environment. Based on this, in accordance with mandatory and non-mandatory regulations issued by authorities, crucial items need to be checked by the watchkeeping team regularly throughout the cargo operation. Hence, crew performance plays a remarkable role in risk analysis and safety investigation. Nevertheless, while identifying the human error contributions in the ship operations the human error should be treated as a combined outcome of some influential factors onboard the ship. Moreover, the failures can sometimes be beyond the control of the crew. Shipper-related issues (misdeclared/undeclared cargo, poor packing or stack, maldistribution of weight), port-related issues (port restrictions, misinformation on the operational process, operator/crane failures, and port storage,) and environmental conditions (weather and sea state) are also the important factors relevant in losing containers. Loading operation involving ballast, hatch cover and lashing operations is a rather complex and challenging process and requires exacting attention to control the process properly. At this point, to avoid unfortunate failures, the operation should be performed in close coordination with the ship crew, loading terminal and planning office. Such failures sometimes occur inevitably. However, the right parameters of risk should be determined and assessed to enhance operational safety.

5.3 Development of a Fault Tree Structure

The container loss risk analysis starts with the development of a logical Fault Tree structure showing the escalation of basic event sequences. The tree provides to establish the structure allowing for fulfilling a thorough understanding of the occurrence of the container loss. Accordingly, a diagrammatic and logical representation of the relationships between each event and the container loss is provided. In this study, the structure of the tree is constructed based on the investigation reports on incidents and literature as well as marine experts' judgement. The CSS Code also provided information on the most crucial basic events as a guide.

The draft of the basic event list is presented to marine experts. Then, the final fault tree is constructed under the supervision of ten marine experts (Table 4.5). Based on this, Table 5.1 identifies the crucial BEs for the container loss risk in containership loading operations.

Table 5.1 : BEs for the loss of container.

Event	Description
TE	Container loss
IE1	Failures associated with cargo
IE2	Failures associated with lashing
IE3	Failures associated with cargo handling
IE4	Packing failure
IE5	Misinformation
IE6	Lashing plan (comply with CSM) violation
IE7	Deck-fitting and lashing equipment failure
IE8	Terminal-induced handling failures
IE9	Stowage plan failure
IE10	Communication failure
IE11	Improper handling
IE12	Improper ballast operation
IE13	Stowage plan application failure
BE1	Incorrect weight distribution
BE2	Mobility due to poor stack
BE3	Inaccurate packing
BE4	Misdeclaration/undeclaration of the actual type/materials of cargo
BE5	Misdeclaration/undeclaration of the actual weight of the container
BE6	Loose lashing gear (lashing bars and turnbuckles)
BE7	Unlocked hatch cleats
BE8	Unlocked twist locks
BE9	Exceeding the recommended lashing forces
BE10	Deck fittings failure
BE11	Broken/bent equipment (twist locks, turnbuckles, bars, etc.)
BE12	Improper equipment for fixed deck fittings
BE13	Gantry/Mobile crane failure
BE14	Operator handling failure
BE15	Port restrictions
BE16	Lack of awareness for wind effect
BE17	Inadequate planning
BE18	Miscommunication as to the operation's actual process
BE19	Lack of communication between crew and stevedore/foreman
BE20	Hook Spreader Usage
BE21	Leakage container loading
BE22	Incorrect special-type container loading
BE23	Missing equipment
BE24	Ballast change failure
BE25	Heeling/ballast system failure
BE26	Exceeding the max. number of containers in each stack
BE27	Exceeding permissible stack weight
BE28	Extreme partial loading
BE29	Exceeding the max GM and stress values
BE30	Neglecting permissible sequences of masses in stacks

5.4 Analysis of Respondents

Since the failure probability data is rather scarce in the container transportation industry, the probability values of failures are calculated by using marine experts' judgements.

The appraisal of human error contribution to operational risks has been carried out with the participation of 10 qualified experts who are highly experienced in containership transportation. 2 out of these marine experts have also working experience as operation managers in container terminals. The selection criteria determined and the profile details of the marine experts are provided in the previous chapter (in section 4.5) in detail.

In this process, the marine experts provide professional judgements expressing the effects of PSFs on human performance to acquire each human error-related basic event probability using the linguistic statements of defined type-2 fuzzy sets.

5.5 Data Derivation

The extent of the human error contribution to the risk of container loss is intended. Accordingly, under the FTA structure, the data derivation process is conducted utilising the IT2FS-SLIM approach to acquire the possibility of each basic event based on the effect of determined PSFs triggering the occurrence of the undesired event. The approach has the capability of generating HEPs in cases where scarce numerical data exists. At this point, the experts provide professional judgement to bridge the gap. Interval type-2 fuzzy sets, in which inputs are expressed in the format of linguistic terms and the outputs are expressed as the crisp values, were preferred since it is capable of handling inexact information in a logically correct manner.

The seven PSFs weighted by marine experts before for containership loading operation have been reutilized in the fault tree analysis since the container loss risk arises as a result of the loading operation failures. Based on this, the marine experts have assigned a rate for each BE identified in Table 5.1, according to the 1-9 liner scale which reflects their relative judgements. In case the PSF has a considerable influence on the BE, 1 is assigned as the highest value. The geometric means of each PSF based on the marine experts' assessments are provided in Table 5.2 below.

Table 5.2 : Geometric means of PSF ratings based on the marine experts' evaluations.

BE	Performance Shaping Factor						
	Stress	Experience	Training	Fatigue	Time L.	Complexity	Safety Culture
1.	7	3	4	4	2	4	3
2.	7	2	4	4	2	5	3
3.	7	2	3	5	2	4	3
4.	6	2	4	5	4	5	3
5.	5	3	3	6	4	5	2
6.	5	2	3	3	2	3	3
7.	4	3	3	2	3	4	2
8.	4	3	4	3	2	4	2
9.	7	2	3	5	3	4	3
10.	7	2	4	3	3	6	3
11.	5	4	4	3	3	4	3
12.	7	3	4	5	4	4	5
13.	6	3	3	4	2	3	3
14.	5	2	3	3	3	5	4
15.	6	3	4	5	4	4	4
16.	6	2	3	5	4	5	3
17.	5	2	2	3	3	3	3
18.	6	3	3	3	2	5	3
19.	7	3	4	4	2	5	4
20.	4	3	3	3	3	3	2
21.	4	2	3	3	3	4	2
22.	6	3	3	4	4	3	3
23.	3	3	4	3	2	4	2
24.	5	2	3	4	3	4	4
25.	5	2	3	5	3	3	3
26.	4	3	3	3	3	3	2
27.	7	2	3	5	4	4	3
28.	7	2	3	5	3	3	3
29.	6	2	3	5	3	3	3
30.	6	3	4	4	3	3	3

Failures related to crew performance, technical and mechanical failures, and equipment functions, as well as environmental factors, are considered altogether for an effective risk determination.

By virtue of the defuzzification and transformation processes, the IT2F-SLIM outcome of each BE is equipped with a probabilistic value. The HEP values for each BE are calculated by using the calibration equation (3.2) of SLIM including a logarithmic relationship to convert SLIs into HEPs. Accordingly, Table 5.3 illustrates each calculated BE probabilistic value. The further steps including analysis of occurrence probability of the top event (loss of the container) of container ship loading operation based on 30 BEs are provided, respectively.

Table 5.3 : Calculated HEP values for each BE.

BE	Calculated		HEP
	SLI	<i>Log -HEP</i>	
1.	3.73	-3.35	4.48E-04
2.	3.75	-3.41	3.86E-04
3.	3.51	-2.73	1.85E-03
4.	3.99	-4.06	8.61E-05
5.	3.89	-3.78	1.65E-04
6.	2.84	-0.86	1.38E-01
7.	2.86	-0.92	1.20E-01
8.	2.95	-1.17	6.72E-02
9.	3.49	-2.68	2.09E-03
10.	3.78	-3.47	3.38E-04
11.	3.76	-3.43	3.70E-04
12.	4.34	-5.04	9.12E-06
13.	3.44	-2.53	2.92E-03
14.	3.40	-2.41	3.87E-03
15.	4.24	-4.77	1.71E-05
16.	3.75	-3.40	3.97E-04
17.	2.88	-0.96	1.09E-01
18.	3.40	-2.41	3.91E-03
19.	3.84	-3.64	2.27E-04
20.	3.04	-1.40	3.95E-02
21.	2.87	-0.94	1.14E-01
22.	3.46	-2.59	2.58E-03
23.	2.87	-0.95	1.13E-01
24.	3.40	-2.42	3.83E-03
25.	3.41	-2.45	3.52E-03
26.	3.04	-1.43	3.76E-02
27.	3.74	-3.37	4.22E-04
28.	3.58	-2.92	1.21E-03
29.	3.50	-2.71	1.94E-03
30.	3.58	-2.92	1.19E-03

5.6 Probabilistic Risk of Container Loss

This section performs probabilistic risk analysis for container loss by systematically predicting human error contributions to the operational risks. To achieve this purpose, in the constructed FT, 30 basic events that will be effective in the realization of the top event have been determined. At this point, three main events that cause the undesired top event are identified as container loss in the fault tree: failures associated with cargo (IE01), failures associated with lashing (IE02), and failures associated with cargo handling (IE03). Having one of these three main intermediate events is sufficient for container damage to occur. Therefore, IE01, IE02 and IE03 are linked to the top event with the “OR” gate. Accordingly, Figure 5.1 depicts the FT diagram for container loss during loading operation in maritime transportation.

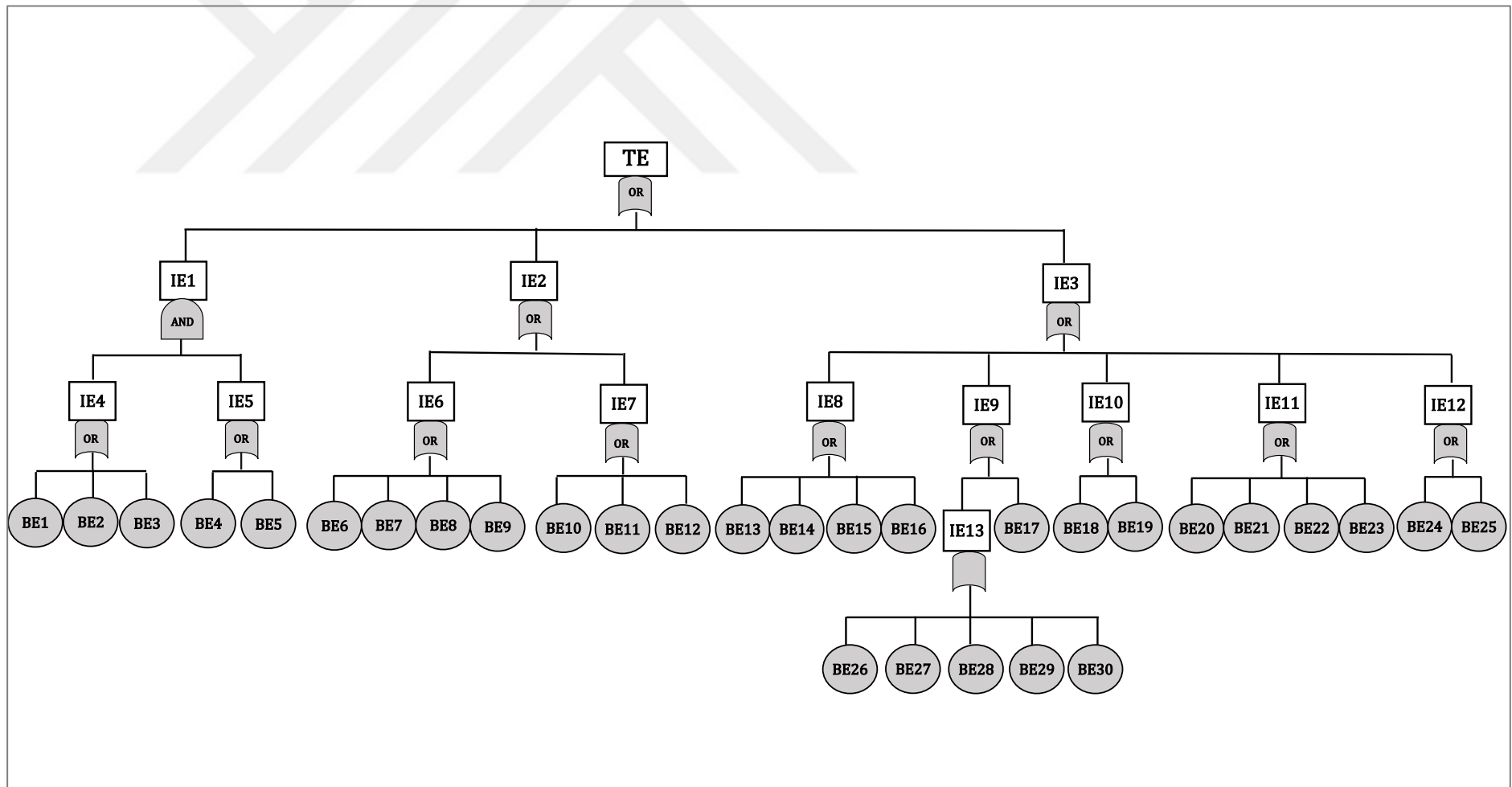


Figure 5.1 : Structure of FT for container loss throughout the cargo operation.

According to FT structure and logic gates, the occurrence probability of the TE (container loss) is calculated by applying equations (3.10) and (3.12). Based on the results, the occurrence probability of TE was found to be 5.54E-01. MCSs, their occurrence probabilities, and the V-FIM list of MCSs that are calculated by respectively applying equations (3.13), (3.14), and (3.15) are depicted in Table 5.4 below.

5.7 Extended Discussion

The assessment of human error probabilities and their contribution to operational risks is the focal point of the study. However, the latent elements, such as organizational, operational, and internal factors that could influence crew performance during cargo handling operations should not be ignored. At this point, the effect of PSFs relating to the task, individuals or working environment was totally considered while calculating the HEP values in this study.

Based on the results, safety culture (0.171), experience (0.165), fatigue (0.165), and time limitation (0.158) were found to be the critical PSFs that highly influencing crew performance throughout the containership loading operation process. Further, an investigation report (Acejo et al, 2018) analysing a total of 693 accident reports to identify the causes of maritime accidents in the period 2002-2016 concluded that in terms of contributory factors identified by accident investigators across all accident types, inadequate training/experience (11.4%) and fatigue (7.5%) were the noteworthy factors lead to accidents. At this point, the obtained results commonly match with the report's results. Figure 5.2 illustrates the comparative representation of weights for PSF. In this case, as loading operation is a routine process for seafarers, stress (0,107) was not perceived by the marine experts to be highly influential. Similarly, the responsible crew is of qualifications, skills and knowledge related to the operational process. Thereby, the complexity was assessed to be a less influential PSF on crew performance compared to others. In the light of the calculated HEP values for each sub-task of loading operation, the findings point out that the safety performance of crew declines and error probability increases drastically towards the end of the operation process. Since numerical data scarcity is one of the most critical factors in maritime transportation, there is no clear standard for classifying the human error probabilities as "High" or "Low".

Table 5.4 : Ranking of BEs according to Fussell-Vesely importance.

Basic Events	Failure Probability of BEs	Number of MCS	MCS Elements	FV-I	Ranking
BE1	4.48E-04	3	BE1, BE1BE4, BE1BE5	4.48E-04	20
BE2	3.86E-04	3	BE2, BE2BE4, BE2BE5	3.86E-04	23
BE3	1.85E-03	3	BE3, BE3BE4, BE3BE5	1.85E-03	17
BE4	8.61E-05	4	BE4, BE1BE4, BE2BE4, BE3BE4	8.65E-05	28
BE5	1.65E-04	4	BE5, BE1BE5, BE2BE5, BE3BE5	1.65E-04	27
BE6	1.38E-01	1	BE6	1.38E-01	1
BE7	1.20E-01	1	BE7	1.20E-01	2
BE8	6.72E-02	1	BE8	6.72E-02	6
BE9	2.09E-03	1	BE9	2.09E-03	15
BE10	3.38E-04	1	BE10	3.38E-04	25
BE11	3.70E-04	1	BE11	3.70E-04	24
BE12	9.12E-06	1	BE12	9.12E-06	30
BE13	2.92E-03	1	BE13	2.92E-03	13
BE14	3.87E-03	1	BE14	3.87E-03	10
BE15	1.71E-05	1	BE15	1.71E-05	29

Table 5.4 (continued) : Ranking of BEs according to Fussell-Vesely importance.

Basic Events	Failure Probability of BEs	Number of MCS	MCS Elements	FV-I	Ranking
BE16	3.97E-04	1	BE16	3.97E-04	22
BE17	1.09E-01	1	BE17	1.09E-01	5
BE18	3.91E-03	1	BE18	3.91E-03	9
BE19	2.27E-04	1	BE19	2.27E-04	26
BE20	3.95E-02	1	BE20	3.95E-02	7
BE21	1.14E-01	1	BE21	1.14E-01	3
BE22	2.58E-03	1	BE22	2.58E-03	14
BE23	1.13E-01	1	BE23	1.13E-01	4
BE24	3.83E-03	1	BE24	3.83E-03	11
BE25	3.52E-03	1	BE25	3.52E-03	12
BE26	3.76E-02	1	BE26	3.76E-02	8
BE27	4.22E-04	1	BE27	4.22E-04	21
BE28	1.21E-03	1	BE28	1.21E-03	18
BE29	1.94E-03	1	BE29	1.94E-03	16
BE30	1.19E-03	1	BE30	1.19E-03	19

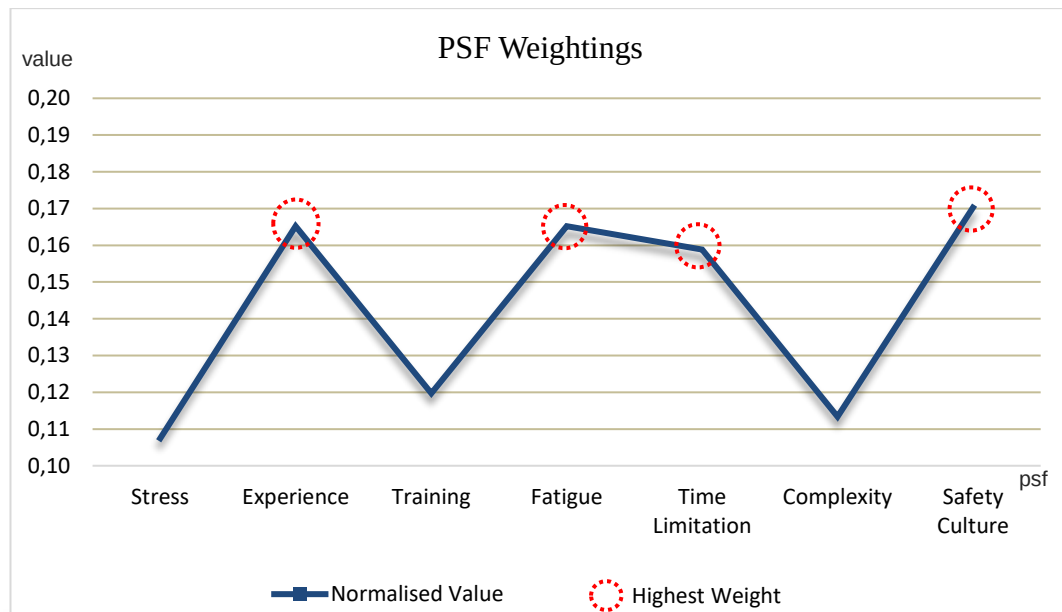


Figure 5.2 : Comparative representation of weight values for PSFs.

However, the average HEP value for each process onboard containership has been considered. Based on this, the values above average HEP value are considered as High HEP values.

In view of the five main processes of the loading operation, it appears that the "pre-arrival" process contains the sub-tasks with the lowest HEP values, relatively. On the other hand, contributory sub-tasks to increase HEP of the "pre-arrival" process is 1.3 (1.95E-02) (Check the provisional list of dangerous goods) and 1.4 (1.59E-02) (Check if the stowage plan is in accordance with the requirements of the IMDG Code) respectively. IMDG type cargoes require higher precautions for handling to prevent massive accidents such as explosion and fire and ensure the safety of the crew, ship and port facility. Relevant parts of both SOLAS and MARPOL regulating the carriage of dangerous goods and marine pollutants in sea-going ships are included in the IMDG Code which is a legal instrument. The code referencing the segregation of incompatible substances was developed for the transport of dangerous goods covering such matters as packing, container traffic and stowage.

The most contributory sub-task (6.45E-02) to increase HEP of the "before loading" process is 2.2 (Make sure that auto-heeling pump is actively running before cargo operation). A containership can heel due to the strong winds and uneven cargo loading during operation. However, heeling is rather risky and the most common cause is uneven and extreme partial loading. The anti heeling system of a ship automatically

detects the heeling angle of the ship and compensates immediately. Hereby, the cargo handling operation continues without stopping in between for list correction. Therefore, the heeling pump should be activated absolutely before cargo operation starts. However, the port period involves extensive and simultaneous activities. At this point, some factors may force the responsible crew to neglect to carry out this sub-task. The graphical representation of comparative HEP values for the first two processes of the loading operation is depicted in Figure 5.3 below.

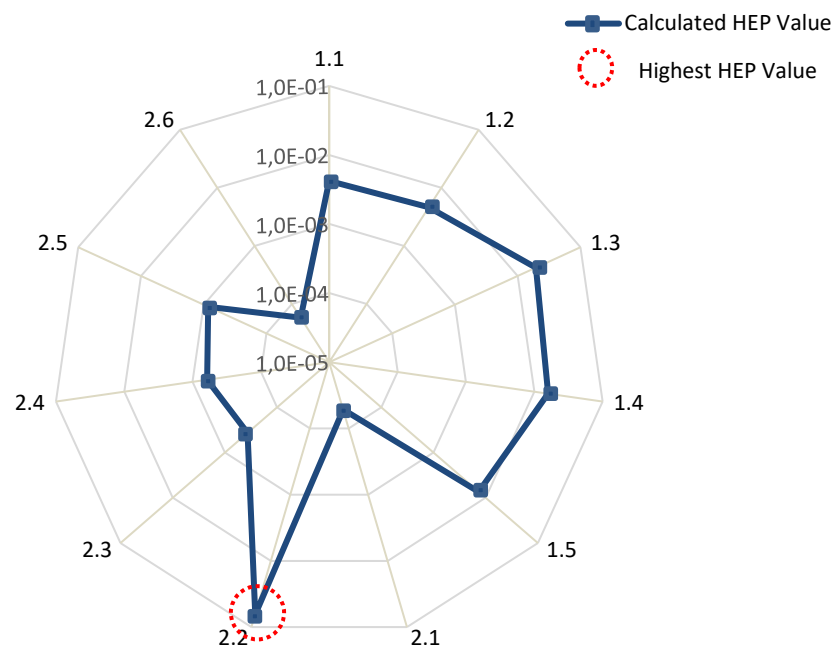


Figure 5.3 : Comparative representation of HEP values for sub-tasks of "pre-arrival" and "before loading" process.

As for the "during loading" process, 3.1.5 (Be aware of the risks of lashing operations on bays at which cargo operations continue) is the most contributory sub-task ($1.91\text{E}-01$) to increase HEP of this process. The lashing operation requiring attention is a crucial activity that should be meticulously carried out in compliance with CSM during operation. Besides its significance, it is a complex, time-consuming, and tiring activity. Nowadays, a high volume of goods can be handled at once especially in significant container terminals of large ports. But, that limited time at the port increases complexity for seafarers and makes them more prone to error is obvious. At this point, safety culture, limited time, and complexity were evaluated as dominant PSFs by the marine experts for the related sub-task. The responsible crew continue to carry out lashing on bays at which the loading operation continues with the worry of not

completing the task in time, although that lead to serious risks for human life and port facilities.

3.2.14 (Check if the leakage containers on board) is the other significant sub-task (1.14E-01) increasing the overall HEP of the "during loading" process. Leakage from containers is a significant problem in the storage and transport of containers and one of the most important goals of safe container handling is to minimize the occurrence probability of leaks or any container damage. An essential part of the planning is the confirmation that the permissible sequences of masses in stacks are not exceeded. At this point, the weight of the container become lighter as time went by and as the leakage continues. Further, leakage may corrode other stacked containers or may produce toxic or inflammable fumes if especially contain dangerous goods. Tragically, both condition results in container loss due to stack collapse or fire. The major cause of leakage is rough and imprecise container handling that causes structural damage such as puncturing or abrasion during cargo operation, in general. Therefore, each container stowed should be kept under strict control against any leakage throughout the loading operation. However, loading operation consists of extensive activities that request responsible crew to perform different tasks and keep caution on the other issues at the same time. Checking of the stacked containers against leakage might be ignored due to lack of experience and time. Whereas, each container stowed should be kept under strict control throughout the loading operation. If any leakage is detected, the container should not be accepted on board or should be discharged immediately after noticing. Fatigue, training, and safety culture were also identified to be influential PSFs by the marine experts for sub-task 3.2.14.

Similarly, the HEP value (7.45E-02) of sub-task 3.2.17 (Inform the charterer and management office if the container is heavily damaged) is obtained rather high when considering the others in this process of loading operation. When a heavily damaged container is observed, the warnings should be made in time to take precautions earlier. Nevertheless, some necessary actions might be ignored due to increasing stress and panic. Besides, financial and commercial concerns might also arise. Based on this, stress, experience, and safety culture were determined as the crucial PSFs that force crew to make errors by marine experts for this sub-task. At this point, within ship management, an effective safety culture provides high awareness of safety issues at all

levels of handling operations. The graphical representation of comparative HEP values for the "during loading" process of the operation is depicted in Figure 5.4 below.

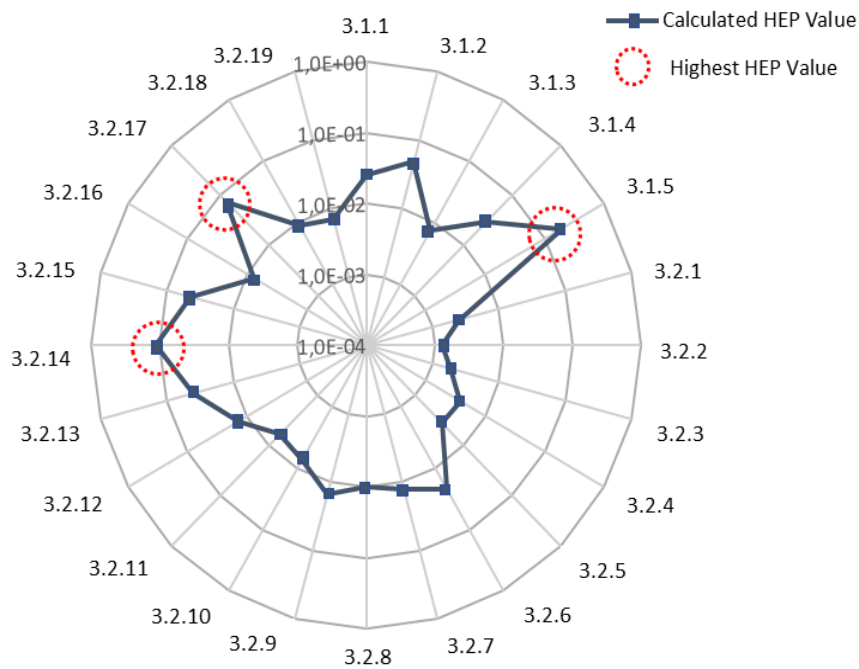


Figure 5.4 : Comparative representation of HEP values for sub-tasks of "during loading" process.

Considering each process of the loading operation, the "after loading" and "pre-departure" processes were found to be the most contributory processes consisting of the sub-tasks with the highest HEPs to increase the criticality of the operation. The obtained results indicated that towards the end of the operational process, the HEP increases with the effect of PSFs. At this point, 4.2 (1.03E-01) (Confirm that all containers are loaded in accordance with the planned stow), 4.5 (1.13E-01) (Inspect that all lashing equipment are exact/not missing), 4.8 (1.20E-01) (Check if the cleats on all sides of all hatch covers are locked), and 4.9 (1.81E-01) (Check if the lashing operation is carried out in compliance with Cargo Securing Manuel) were found to be the sub-tasks with higher HEP values compared to other tasks in 4th process of the operation.

With the completion of the loading, crucial items need to be checked by the watchkeeping team cautiously. Control of the lashing operation in detail is one of them. Unlocked hatch cover cleats and loose lashings can lead a container stack to move as the ship rolls and force on the adjacent stacks while the vessel is underway. Besides, as the ship rolls, the forces on the adjacent stacks gradually increase and put

the lashings under additional load. Each subsequent failure results in container loss due to stack collapse. In this situation, with the increasing influence of the factors such as fatigue and limited time, the crew becomes more prone to errors, unavoidably.

The other crucial item is the loading in accordance with the bay plan. An essential part of the planning is the confirmation that allowable stack weights, permissible sequences of masses in stacks, the max GM and stress values are not exceeded. Based on this, 5.2 (2.41E-01) (Make sure that auto-heeling pump is properly deactivated), 5.3 (2.64E-01) (Make sure that the GM value complies with the limit of the minimum required GM value that given by loadmaster +40 cm limit), 5.4 (2.50E-01) (Check if sea condition %95 stress is exceeded), and 5.5 (1.71E-01) (Make sure that stress values are calculated and signed) were found to be the sub-tasks with the highest HEP values in the last process of the operation.

The "pre-departure" process requires extensive activities besides stability checks such as documentation for authority permission, checks for security (stowaways, watertight doors), checks for safety (LSA, navigational equipment) ensure that the ship is ready to seaworthy before departure for the next destination. Hence, with the increasing influence of the PSFs and complexity, the success likelihood of the crew performance tends to decrease. The graphical representation of comparative HEP values for the last two processes of the operation is depicted in Figure 5.5 below.

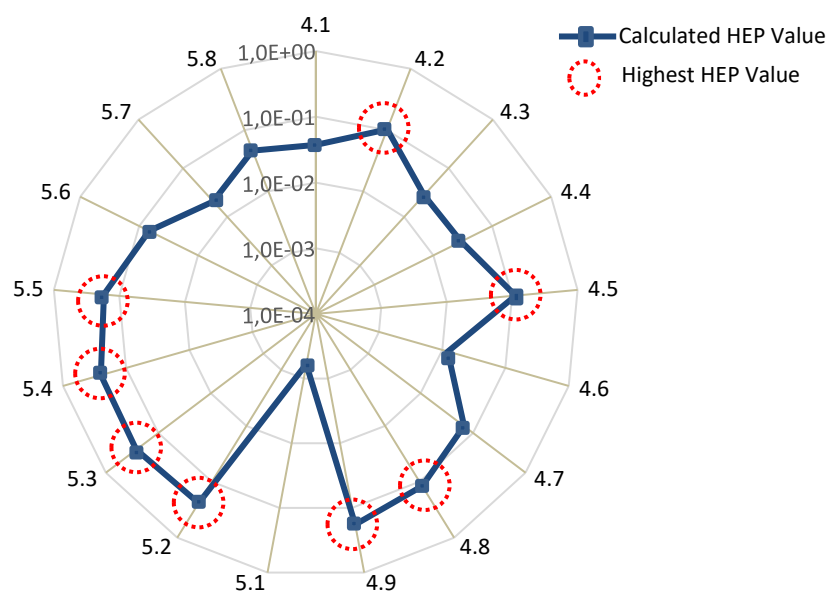


Figure 5.5 : Comparative representation of HEP values for sub-tasks of "after loading" and "pre-departure" process.

Risk analysis provides a systematic way of predicting the occurrence of an undesired event (TE) by integrating both qualitative and quantitative information of potential events, causes, and consequences (Akyuz et al, 2020). From a risk-reduction standpoint, a comprehensive risk analysis utilising state-of-the-art techniques and approaches can help to identify the safety level of the operation. Accordingly, the critical sub-tasks with the highest HEP values can be categorised into the high-risk operational process demanding strict precautions and frequent control. Unless the risk is not reduced to the desired level, the risk reduction measures involving all parameters should be reviewed again to enhance operational safety in the maritime transportation industry.

One of the most important objectives of safe container handling is therefore to detect the potential failures caused by any factor before an occurrence. At this point, a comprehensive risk analysis for container loss was carried out to predict crew error contributions to operational risks.

In the light of risk analysis on container handling during loading operation, the occurrence probability of the top event (container loss) was calculated as $5.54E-01$ (0.554). The result indicates that 55 out of 100 cases may result in container loss due to human error contribution during a loading operation.

Under the FT structure, to achieve TE occurrence probability, the possibility of each basic event that includes human errors resulting in container loss was subsequently acquired. In view of the extended calculations, BE6 ($1.38E-01$) (Loose lashing gear), BE7 ($1.20E-01$) (Unlocked hatch cleats), and BE21 ($1.14E-01$) (Leakage container loading) were apparently found to be the most contributory basic events increasing the risk of container loss, respectively. At the same time, sub-task 3.2.14 (Check if the leakage containers on board), sub-task 4.8 (Check if the cleats on all sides of all hatch covers are locked), and sub-task 4.9 (Check if the lashing operation is carried out in compliance with Cargo Securing Manuel) were already observed with higher HEP values while producing human error probabilities with the consideration of PSF effects. Based on this, obtained results clarify how crucial human errors are in triggering ship disasters.

The MCSs which are the smallest combination of the BEs are also critical events triggering the occurrence of the TE. They are rather useful to determine the structural

vulnerability of the system. Therefore, prior to the quantification of the container loss occurrence probability, all BEs were combined to derive the MCSs based on the fault tree logic. At this point, BE4 (Misdeclaration/undeclaration of the actual type/materials of Cargo) and BE5 (Misdeclaration/undeclaration of the actual weight of the container) were the basic events that derive the most MCSs (4 MCSs for each) compared to others.

The consequences of misdeclared/undeclared cargo can be catastrophic in some cases, an example being the explosion onboard MSC Flaminia (Balisampang et al, 2018; Wróbel et al, 2017). The disastrous explosion was followed by a fire that resulted in the death of three crew members as well as heavily damaged the hull structure. The fire onboard the MSC Flaminia was caused by the auto-polymerization and ignition of the chemical called Divinylbenzene 80%. To that extent, the correct stowage of the containers with Divinylbenzene was vital. However, they have actually loaded under the deck since the containers were labelled as a marine toxin rather than an explosive hazard. Based on this, the temperature was controlled neither during carriage prior to loading on the ship nor throughout the operation.

The disastrous explosion that occurred in a cargo hold of containership Hanjin Pennsylvania (Balisampang et al, 2018; Ellis, 2010; Ren, 2009) is the other unfortunate example of the importance of the subject. The containers filled with fireworks have been misdeclared on the manifest. Hence, the containers listed as having a non-hazardous content were incorrectly stacked at the very bottom of the hold since they have not been marked and segregated as appropriate. The ship stayed afloat but the disaster resulted in the death of two crew members, tragically.

Then again, a report of the preliminary enquiry into the explosion and fire onboard the Sea Elegance containership in 2003 stated that the fire originated in a container containing dangerous inflammable matter (Calcium Hypochlorite) that had not been declared in the manifest (South African Maritime Safety Authority, 2004). The disaster resulted in the death of one crew member and extensive vessel and cargo damage.

Similarly, the major explosion occurred in a cargo hold, aft of the accommodation of Hyundai Fortune (Balisampang et al, 2018; Ellis, 2011; Ellis 2010). The explosion was followed by a massive fire that spread through the stern of the ship, the accommodation, and the container stacks in front of the accommodation.

Approximately, 60 to 90 containers fell into the ocean when the explosion occurred. The cause of the fire was a container loaded with petroleum-based cleaning fluids that was incorrectly stowed near the engine room. The US House of Representatives Homeland Security Appropriations Committee stated that the shipper misdeclared the hazardous nature of this cargo to the Hyundai Fortune to avoid the special handling fees associated with transporting dangerous materials (Flynn, 2008).

The consequences of underdeclared weights of containers led to a serious failure of a containership, an example being the hull fracture of MSC Napoli (Wróbel et al, 2017; Parunov et al, 2014; Guitart et al, 2008). Essentially, the vessel encountered heavy seas that cause her to pitch heavily when on the passage in the English Channel. Right after, a catastrophic failure was suffered from her hull in way of her engine room and then broke in two tragically. The report by the Marine Accident Investigation Branch (MAIB, 2008) has identified a number of factors that contributed to the hull structure failure including the underdeclared weight of containers. All of MSC Napoli's containers were weighed again for investigation when they were removed from her. Nearly all the containers loaded below decks had been exposed to water absorption. In other respects, the weights of 137 of 660 containers stowed on deck, which had remained dry, were also more than 3 tonnes different from declared weights. To sum up, the total weight of the 137 containers was 312 tonnes heavier than on the manifest. The load on the hull have increased by whipping effect and her hull did not have sufficient buckling strength in way of the engine room, already. All of these failures have played a crucial role in the occurrence of this catastrophic event.

From that, it is concluded that potential hazards can easily develop in combination with other cargo or stowage positions exposed to heat in the hold. The impacts of temperature, moisture and other unavoidable stresses on hazardous goods are not easily noticeable and often late well understood of damaging. It is also known that containerships invariably sail very close to the permissible seagoing maximum bending moments. On the other hand, the undeclared weight is of the significant potential to lead vessels to exceed these values and the stresses acting on containerships should be accurately controlled to prevent serious accidents and losses.

Ensuring that dangerous goods are properly packed, correctly prepared and documented for sea transport is of vital importance for maritime transportation safety (Ellis, 2011). Even though undeclared/misdeclared goods have been identified as a

main contributing factor in several serious accidents, there are still deficiencies with respect to regulations (Porter, 2008).





6. CONCLUSIONS AND RECOMMENDATIONS

6.1 Conclusive Remarks and Recommendation

The maritime transportation industry has a continuing interest in safe cargo operations due to the growing global concern over marine casualties and disasters. As the considerable amount of tragic events and container shipping disasters caused the worst maritime environmental disasters last two decades, container transportation has become even more important for maritime authorities. Despite the technological improvements, seafaring still remains a dangerous occupation. Each operational activity performed onboard ships include high risk due to the nature of work. At this point, concern for ship and port facility safety, the preservation of the marine environment, and the high cost of accidents make safe and secure containership cargo operations a crucial matter.

Identifying the risks factors and minimizing the threats to an acceptable level is vital to enhance operational safety and to manage risks. Technical, mechanical, and structural failures and environmental factors are prevalent causes increasing the marine accident risk. However, according to the conclusions drawn by the accident reports human error is the most frequent and major cause of these marine casualties. Hence, human errors should be the focal point of the quantitative risk analysis in maritime operations.

The evaluation of HEPs in the maritime transportation industry is onerous due to the numerical data scarcity. Besides, the applied HRA methods are insufficient to overcome vagueness and inconsistency. The thesis points to the overriding importance of human performance in safe operations and proposes a hybrid approach through incorporating FTA and interval type-2 fuzzy-based SLIM to evaluate the HEPs and their contribution to risks as well as the criticality of the loading operation activities in a container terminal. In this context, SLIM is utilised to systematically estimate HEP values for each designated task whilst IT2FS deals with vagueness and subjectivity in the process of using experts' judgements. Thereby, a detailed account of human error

probability, all the relevant factors and contributory causes are identified in detail. Further, FTA performs a comprehensive risk analysis and evaluate the criticality of the operational activities.

In view of the extended risk analysis on container handling operation, the results obtained are considered satisfactory and in the range of expectation. The occurrence probability of the container loss was found to be 5.54E-01 which is considerably high. In addition, that the proposed hybrid approach can effectively be applied for determining the vulnerabilities and critical human errors in the operational process is concluded.

Based on the analysis, there are some determined events where improved safety culture and training practices could prove effective in loss prevention. For instance, concerning events where loose lashing gear and unlocked hatch cleats are identified as major basic events triggering the occurrence of container loss, having greater risk awareness, being acted upon instructions of codes, and more careful qualified and experienced crew selection for the task could serve to reduce errors in the future. Further, the critical conditions relate to lashing operation should be regularly emphasized by conducting safety meetings onboard ship. All aspects of operational risks should be proactively identified. Being risk aware provides that the responsible crew is potentially able to prevent error and recognize subsequent consequences.

The other significant basic event was on the subject of operational checks due to human omission in leakage container loading. The crew in charge should be able to better recognize risks before they become issues. At this point, a detailed checklist to be followed during the loading operation can help the crew to remind the further precautions to be taken.

A better understanding of factors underlying human errors will guide safety managers on the improvement of operational safety. In this thesis, the significance of various factors was also determined as causing human errors that should be certainly addressed including ineffective safety culture, inadequate experience, fatigue, and limited time. The obtained results indicate that the management office's commitment to safety is highly effective on the crew's safety attitudes towards the task. In this context, barriers to effective action, lack of risk communication, and training tools that help improve risk awareness should be discussed with simultaneous involvement of crew, safety

inspectors, and designated person ashore (DPA) to provide better proactive solutions. Further, maritime authorities, key industry stakeholders and shipping companies around the world should invest a considerable amount of resources in investigating the vulnerabilities of the shipboard operations and causes of casualties resulting from human error to enhance maritime transportation safety. The shipping companies should also consider the need to recentre their safety culture around the human element, increasing their proactivity in ensuring operational safety. Through support from risk management professionals shipping companies should be ready for any crisis caused to marine incidents across the globe.

6.2 Contributions to Academic Literature

In the light of literature, although there are some researches presented addressing the human reliability assessments, the studies predicting the likelihood of human error in critical shipboard operations are rather limited. Based on the gap, this thesis systematically evaluates the role of the human factor in a real-time loading operation onboard a container ship and analysis the risks of human-oriented failures, meticulously. The contributory items of the thesis to academic literature can be highlighted as follows.

- A wide range of literature along with the human error probability assessment in the maritime transportation industry as well as other high-risk industries is reviewed.
- IT2FS integration into the SLIM technique, which is a quantitative human error probability assessment method, is introduced.
- Marine-specific HEP values, in accordance with an advanced methodological framework including accident causation, expert judgement, PSF weighting and rating are derived.
- FTA integration into IT2FS based SLIM method, which is a new hybrid approach for human error contribution to risk in containership loading operations.
- Comprehensive marine casualties and incidents investigation to determine the contributory causes, circumstances and effects of the accident, is provided.

- A flexible and practical approach to detecting vulnerabilities in the operational process is precisely developed.
- Both qualitative and quantitative data in maritime transportation safety is provided.

6.3 Contributions to Maritime Transportation Industry

There have been serious accidents involving the maritime transport of containerized goods in recent years. The industry seeks proactive solutions to minimise human error in marine accidents since human is the most contributory factor that increases operational risks. Nevertheless, although comprehension of the extent to which human error contributes to accidents is the key issue, the necessary effort has not been devoted to analysing risks that are related to critical human error in the maritime industry. Since the safety of the marine transport operation depends on the reliability and safety performance of the humans in charge, the thesis quantifies the potential human-related failures in loading operations and provides an insight into what measures may be necessary to avoid future container losses. At this point, the contributory items of the thesis to the maritime transportation industry can be highlighted as follows.

- A quantitative hybrid approach systematically evaluating human error probabilities in critical shipboard operations is developed to enhance safety.
- The systematic PSFs which mainly contributed to the potential human errors rather than all PSFs are identified.
- Numerical evidence attesting to the importance of developing valid industry-specific measures of operational safety is presented.
- Probabilistic risk analysis to prevent similar accidents from occurring in the future in the maritime industry is conducted.
- The most contributory failures increasing the level of operational risk and vulnerabilities in the process are determined.
- Recommendations that can recover the vessel from undesired events, stop the event sequence, or mitigate its consequences are presented.

- A reference study addressing the impact of human errors on maritime accidents to provide both theoretical and practical contributions to the industry is presented.

6.4 Research Limitations

One way to enhance safety at sea is to investigate and learn from past disastrous accidents. Based on this, data is a significant part of the study since the findings are utilised as the foundation to be built upon to achieve the main objectives. At this point, one of the fundamental limitations of the thesis is the scarcity of data. Despite the fact that a few techniques are being applied to predict human error probabilities in other high-risk industries, there is no sufficient number of specific methods and researches addressing human errors in the maritime transportation industry. Further, in the framework of the HEP assessment process that should contain both relevant data and real case studies, it is rather difficult to obtain empirical data in the maritime industry.

The scarce human error data in containership operations is the motivation for utilising the expert judgement technique in the thesis. However, several issues have been revealed associated with this technique in recent studies. Especially, subjectivity plays a crucial role in the expert judgements process and causes difficulties in assuring consistency. At this point, IT2FS deals with vagueness and subjectivity in the process of using experts' judgements. Nevertheless, real data should be captured to validate the acquired results.

Since the technique deals with any level of decomposition that the experts are confident to quantify and requires reliance on assessments by domain experts, the expert elicitation process should be carried out with care. In this context, significant criteria are determined to form an expert committee. Meeting the two of the criteria; "Have the required time to perform assessments", and "Available to meet in person during data collection" are the other fundamental limitation of the thesis, in particular. The slightest disagreement and poor communication with the marine experts during the evaluation process could risk the reliability of the obtained results. However, some of the pandemic-related limitations were reasonably foreseen in the thesis research process. Fortunately, a healthy information flow was provided from experienced marine experts in time and transformed into useful information in the data derivation and risk analysis process of the thesis. With the meticulously prepared survey

presented in Figure A.2 (for HEP assessments) and Figure A.3 (for human error-related risk analysis) upon to the real-time containership cargo operation, all process was conducted untroubled as planned.

6.5 Further Research

The focal point of the thesis is the quantitative determination of the human error probabilities and the analysis of human error contributions to operational risks to enhance safety. At this point, the hybrid approach is effectively applied in accordance with the goal. Nonetheless, potential future research may address the respective contributions of human errors to risks by utilising multilevel methods. For instance, IT2FL based SLIM approach can be expanded by integrating a new generation method such as BN to perform a comprehensive risk analysis as well as to compare the results. Future researches may also be enhanced by considering various parameters such as the type, length, and year of built of the vessel.

Besides experts' judgements, the data from the simulation studies of cargo operations can be utilised to determine the probabilities of human errors and the basic events. Based on this, the scenario including probabilistic risk analysis may be supported with a dynamic simulation to produce the top event results obtained. Further, software that analyses human error-related risks to minimize the effect of potential risks that poses a threat to any organization may also be developed for practical use. In order to calculate the failure probability of an undesired event due to individual, technical, mechanical and environmental combinations, a set of numerical simulations may be carried out via risk analysis software.

By virtue of the fuzzification, defuzzification and transformation processes, the marine experts' linguistic variables are converted to acquire crisp values under the IT2F environment in the weighting process of PSFs. As for the PSF rating process, the marine experts nominate a value from 1 to 9 on a linear scale to specify the PSF impact upon the crew performance for the relevant task. At this point, the rating scale may be fuzzified, recalculated and equipped with a crisp value as in the weighting process in potential future research.

REFERENCES

- Abrishami, S., Khakzad, N., Hosseini, S. M., & van Gelder, P.** (2020). BN-SLIM: A Bayesian Network methodology for human reliability assessment based on Success Likelihood Index Method (SLIM). *Reliability Engineering and System Safety*, 193, 106647. doi:10.1016/j.ress.2019.106647.
- Acejo, I., Sampson, H., Turgo, N., Ellis, N., & Tang, L.** (2018). *The causes of maritime accidents in the period 2002-2016*. 18. Seafarers International Research Centre (SIRC), Cardiff University.
- Akyuz, E.** (2015). Quantification of human error probability towards the gas inerting process on-board crude oil tankers. *Safety Science*, 80, 77–86. doi:10.1016/j.ssci.2015.07.018.
- Akyuz, E.** (2016). Quantitative human error assessment during abandon ship procedures in maritime transportation, *Ocean Engineering*, 120, 21–29, doi:10.1016/j.oceaneng.2016.05.017.
- Akyuz, E., and Celik, E.** (2016). A modified human reliability analysis for cargo operation in single point mooring (SPM) off-shore units. *Applied Ocean Research*, 58, 11–20. doi:10.1016/j.apor.2016.03.012.
- Akyuz, E., and Celik, E.** (2017). The role of human factor in maritime environment risk assessment: A practical application on Ballast Water Treatment (BWT) system in ship. *Human and Ecological Risk Assessment*. 24, 653–666. doi:10.1080/10807039.2017.1396184.
- Akyuz, E., and Celik, E.** (2018). A quantitative risk analysis by using interval type-2 fuzzy FMEA approach: the case of oil spill. *Maritime Policy and Management*, 45(8), 979–994. doi:10.1080/03088839.2018.1520401.
- Akyuz, E., Arslan, O., & Turan, O.** (2020). Application of fuzzy logic to fault tree and event tree analysis of the risk for cargo liquefaction on board ship. *Applied Ocean Research*, 101, 102238. doi:10.1016/j.apor.2020.102238.
- Almond, R.** (1992). *An extended example for testing Graphical Belief*. Technical Report 6, Statistical Sciences Inc.
- Antao, P., and C. G. Soares.** (2006). Fault-Tree Models of Accident Scenarios of Ropax Vessels. *International Journal of Automation and Computing*, 2: 107–116.
- Arıcı, S. S., Akyuz, E., & Arslan, O.** (2020). Application of fuzzy bow-tie risk analysis to maritime transportation: The case of ship collision during the STS operation. *Ocean Engineering*, 217, 107960.

- Aydin, M., Camliyurt, G., Akyuz, E., Arslan, O.** (2021). Analysing human error contributions to maritime environmental risk in oil/chemical tanker ship. *Human and Ecological Risk Assessment*. doi:10.1080/10807039.2021.1910011.
- Baalisampang, T., Abbassi, R., Garaniya, V., Khan, F., & Dadashzadeh, M.** (2018). Review and analysis of fire and explosion accidents in maritime transportation. *Ocean Engineering*, 158, 350–366. doi: 10.1016/j.oceaneng.2018.04.022.
- Bea, R. G.** (2001). Risk Assessment and Management of Offshore Structures. *Progress in Structural Engineering and Materials*, 3, 180–187.
- Bell, J., and Holroyd, J.** (2009). *Review of human reliability assessment methods*. Health & Safety Laboratory, 78.
- Calixto, E., Lima, G. B. A., & Firmino, P. R. A.** (2013). Comparing SLIM, SPAR-H and Bayesian Network Methodologies. *Open Journal of Safety Science and Technology*, 3 (02), 31–41. doi:10.4236/ojsst.2013.32004.
- Castiglia, F. and Giardina, M.** (2013). Analysis of operator human errors in hydrogen refuelling stations: Comparison between human rate assessment techniques. *International Journal of Hydrogen Energy*, 38, 1166–1176. doi:10.1016/j.ijhydene.2012.10.092.
- Castillo, O. and Melin, P.** (2008). *Type-2 Fuzzy Log.: Theory and Application*, STUDFUZZ. 223,145-154.
- Castillo, O., Melin, P., Kacprzyk, J., & Pedrycz, W.** (2008). Type-2 Fuzzy Logic: Theory and Applications. *IEEE International Conference on Granular Computing Type-2*. 145–145. doi:10.1109/grc.2007.118.
- Celik, M., and Cebi, S.** (2009). Analytical HFACS for investigating human errors in shipping accidents. *Accident Analysis and Prevention*, 41(1), 66–75. doi:10.1016/j.aap.2008.09.004.
- Chauvin, C., Lardjane, S., Morel, G., Clostermann, J. P., & Langard, B.** (2013). Human and organisational factors in maritime accidents: Analysis of collisions at sea using the HFACS. *Accident Analysis and Prevention*, 59, 26–37. doi:10.1016/j.aap.2013.05.006.
- Chen, L., Wang, G.L., & Meng, H.R.** (1995). Fault tree analysis of an oilwell pump. *Acta Petroleum Sinica*, 16(3), 145–151.
- Chien, S.H., Dykes, A.A., Stetkar, J.W., & Bley, D.C.** (1988). Quantification of Human Error Rates Using a SLIM-Based Approach. *Proceedings of the Institute of Electrical and Electronics Engineers 4th Conference on Human Factors and Power Plants*, 397-302.
- Cohen, S.S.** (2006). Boom Boxes: Containers and Terrorism. In: Haveman, J.D., Shatz, H.J. (Eds.), *Protecting the Nation's Seaports: balancing security and cost*. Public Policy Institute of California, San Francisco, CA. Retrived from <http://www.ppic.org/main/publication.asp?i=698>.
- Cooper S.E., Ramey-Smith A.M., & Wreathall J.** (1996). *A technique for human event analysis (ATHEANA) – technical basis and methodological description*. Upton (NY): Brookhaven National Laboratory; 1996. (US Nuclear Reg- ulatory Commission; report no. NUREG/CR-6350).

- Ćorović, B. M., & Djurovic, P.** (2013). Marine Accidents Researched Through Human Factor Prisma. *PROMET - Traffic&Transportation*, 25(4), 369–377. doi:0.7307/ptt.v25i4.1210.
- Coyne, K., and Mosleh, A.,** (2018). Dynamic probabilistic risk assessment model validation and application - Experience with ADS-IDAC, Version 2.0. *Adv. Concepts Nuclear Energy Risk Assessment and Management*. 45–86. doi:10.1142/9789813225619_0002.
- Deacon, T., Amyotte, P. R., & Khan, F. I.** (2010). Human error risk analysis in offshore emergencies. *Safety Science*, 48(6), 803–818. doi:10.1016/j.ssci.2010.02.013.
- Deacon, T., Amyotte, P. R., Khan, F. I., & MacKinnon, S.** (2013). A framework for human error analysis of offshore evacuations. *Safety Science*, 51(1), 319–327. doi:10.1016/j.ssci.2012.07.005.
- Di, V., Miranda, S., Iannone, R., & Riemma, S.** (2015). A Simulator for Human Error Probability Analysis (SHERPA). *Reliability Engineering& System Safety*, 139, 17–32. doi:10.1016/j.res.2015.02.003.
- DiMattia, D. G.** (2004). *Human error probabiltiy index for offshore platform musters*. (Doctoral dissertation). Halifax, NS, Canada: Dalhousie University.
- DiMattia, D. G., Khan, F. I., & Amyotte, P. R.** (2005). Determination of human error probabilities for offshore platform musters. *Journal of Loss Prevention in the Process Industries*, 18(4-6), 488–501. doi:10.1016/j.jlp.2005.07.021.
- Ellis, J.** (2010). Undeclared dangerous goods-Risk implications for maritime transport. *WMU Journal of Maritime Affairs*, 9(1), 5–27. doi: 10.1007/BF03195163.
- Ellis, J.** (2011). Analysis of accidents and incidents occurring during transport of packaged dangerous goods by sea. *Safety Science*, 49, 1231–1237. doi: 10.1016/j.ssci.2011.04.004.
- Embrey, D. E., Humphreys, P.C., Rosa, E.A., Kirwan, B., & Rea, K.** (1984). *SLIM-MAUD: an approach to assessing human error probabilities using structured expert judgement*. NUREG/CR-3518. US Nuclear Regulatory Commission, Washington DC.
- Embrey, D. E., Kontogiannis, T., & Green, M.** (1994). *Guidelines for Preventing Human Error in Process Safety*. Center for Chemical Process Safety, American Institute of Chemical Engineers, New York.
- Erdem, P., and Akyuz, E.** (2021). An interval type-2 fuzzy SLIM approach to predict human error in maritime transportation. *Ocean Engineering*, 232, 109161. doi:10.1016/j.oceaneng.2021.109161.
- Ernstern, J. and Nazir, S.** (2018). Human Error in Pilotage Operations. *TransNav, the International Journal on Marine Navigation and Safety of Sea Transportation*, 12 (1), 49-56.

- Faaui, T. N., Morgan, T. K. K. B., & Hikuroa, D. C. H.** (2017). Ensuring objectivity by applying the Mauri Model to assess the post-disaster affected environments of the 2011 MV Rena disaster in the Bay of Plenty, New Zealand. *Ecological Indicators*, 79, 228–246. doi:10.1016/j.ecolind.2017.03.055.
- Fan, L., Zheng, L., & Luo, M.** (2020). Effectiveness of port state control inspection using Bayesian network modelling. *Maritime Policy and Management*, 1–18. doi:10.1080/03088839.2020.1841913.
- Gertman, D., Blackman, H., Marble, J., Byers, J., & Smith, C.** (2005). *The SPAR-H human reliability analysis method*. Idaho National Laboratory.
- Gibson, W.H., Mills, A.M., Smith, S., & Kirwan, B.K.** (2012). *Railway Action Reliability Assessment, a Railway Specific Approach to Human Error Quantification*. Rail Human Factors. Supporting Reliability, Safety and Cost Reduction. Taylor & Francis.
- Goerlandt, F., Montewka, J., Kuzmin, V., & Kujala, P.** (2015). A risk-informed ship collision alert system: Framework and application. *Safety Science*, 77, 182–204. doi:10.1016/j.ssci.2015.03.015.
- Groth, K.M. and Swiler, L.P.** (2012). Use of a SPAR-H bayesian network for predicting human error probabilities with missing observations. *11th Int. Probabilistic Safety Assessment and Management Conference Annual. Eur. Saf. Reliab. Conf. 2012, PSAM11 ESREL 2*, 1009–1018.
- Grozdanovic, M.** (2005). Usage of Human Reliability Quantification Methods. *International Journal of Occupational Safety and Ergonomics*, 11(2), 153–159. doi:10.1080/10803548.2005.11076644.
- Guitart, C., Frickers, P., Horrillo-Caraballo, J., Law, R. J., & Readman, J. W.** (2008). Characterization of Sea Surface Chemical Contamination after Shipping Accidents. *Environmental Science & Technology*, 42(7), 2275–2282. doi:10.1021/es703125e.
- Hannaman G, Spurgin A, & Lukic Y.** (1984). *Human cognitive reliability model for PRA analysis*. Palo Alto (CA): Electronic Power Research Institute; 1984.
- Harrald, J.R., Mazzuchi, T.A., Spahn, J., Van Dorp, R., Merrick, J., Shrestha, S. & Grabowski, M.** (1998). Using system simulation to model the impact of human error in a maritime system. *Safety Science*, 30, 235–247. doi:10.1016/S0925-7535(98)00048-4.
- He, X., Wang, Y., Shen, Z., & Huang, X.** (2008). A simplified CREAM prospective quantification process and its application. *Reliability Engineering & System Safety*, 93, 298–306. doi:10.1016/j.ress.2006.10.026.
- Hollnagel, E.** (1998). *Cognitive Reliability and Error Analysis Method (CREAM)*. Elsevier, Amsterdam.
- Hwang, D. J.** (2020). The IMO Action Plan to Address Marine Plastic Litter from Ships and Its Follow-Up Timeline. *Journal of International Maritime Safety, Environmental Affairs, and Shipping*, 1–8. doi:10.1080/25725084.2020.1779428.

- IMO** (2003). *Human Element Vision, Principles and Goals for the Organization*, Resolution A.947(23) Adopted on 27 November 2003 (Agenda item 17).
- Islam, R., Abbassi, R., Garaniya, V., & Khan, F. I.** (2016). Determination of human error probabilities for the maintenance operations of marine engines. *Journal of Ship Production and Design*, 32(4), 226–234. doi:10.5957/JSPD.32.4.150004.
- Islam, R., Abbassi, R., Garaniya, V., & Khan, F.** (2017a). Development of a human reliability assessment technique for the maintenance procedures of marine and offshore operations. *Journal of Loss Prevention in the Process Industries*, 50, 416–428. doi:10.1016/j.jlp.2017.10.015.
- Islam, R., Yu, H., Abbassi, R., Garaniya, V., & Khan, F.** (2017b). Development of a monograph for human error likelihood assessment in marine operations. *Safety Science*, 91, 33–39. doi:10.1016/j.ssci.2016.07.008.
- Islam, R., and Yu, H.** (2018). Human Factors in Marine and Offshore Systems. In *Offshore Process Safety* (1st ed., Vol. 2). Elsevier Inc. doi:10.1016/bs.mcps.2018.04.002.
- Jae, M. S., and Park, C. K.** (1995). A new dynamic HRA method and its application. In *Journal of the Korean Nuclear Society*, 27 (3)3, 292–300.
- Jo, G. W.** (2020). The need for international policy regarding lost containers at sea for reducing marine plastic litter. *Journal of International Maritime Safety, Environmental Affairs, and Shipping*, 4(3), 80–83. doi:10.1080/25725084.2020.1792392.
- Kahraman, C., Oztays,i, B., Sari, I.U., Turanoglu, E.** (2014). Fuzzy analytic hierarchy process with interval type-2 fuzzy sets. *Knowledge-Based Systems*, 59, 48–57. doi:10.1016/j.knosys.2014.02.001.
- Karahalios, H.** (2015). *The Management of Maritime Regulations*. Routledge.
- Kelman, J. B.** (2008). Hazards in the maritime transport of bulk materials and containerized products. *Loss Prevention Bulletin*, 203, 28–36.
- Khan, F. I., and Abbasi, S. A.** (2000). Analytical simulation and PROFAT II: A new methodology and a computer automated tool for fault tree analysis in chemical process industries. *Journal of Hazardous Materials*, 75(1), 1–27. doi:10.1016/S0304-3894(00)00169-2.
- Khan, F. I., Amyotte, P. R., & DiMattia, D. G.** (2006). HEPI: A new tool for human error probability calculation for offshore operation. *Safety Science*, 44(4), 313–334.
- Kirwan, B.** (1994). *A Guide to Practical Human Reliability Assessment*. Taylor & Francis. Pp: 21-35.
- Kirwan, B.** (1997). The validation of three Human Reliability Quantification techniques -THERP, HEART and JHEDI: Part III - practical aspects of the usage of the techniques. *Applied Ergonomics*. 28(I), 27-39.

- Kirwan, B., and Gibson, W.H.** (2008). *Human Reliability Assessment (CARA) Development for EUROCONTROL*, Q07/22268NC.
- Kirwan, B., Gibson, H., Kennedy, R., Edmunds, J., Cooksley, G., & Umbers, I.** (2004). Nuclear Action Reliability Assessment (NARA): A Data Based HRA Tool. *Probabilistic Safety Assessment and Management*: 1206 - 1211.
- Konstandinidou, M., Nivolianitou, Z., Kiranoudis, C., & Markatos, N.** (2006). A fuzzy modeling application of CREAM methodology for human reliability analysis. *Reliability Engineering & System Safety*, 91, 706–716. doi:10.1016/j.ress.2005.06.002.
- Kornecki, A. J., and Liu, M.** (2013). Fault tree analysis for safety/security verification in aviation software. *Electronics*, 2(1), 41–56. doi:10.3390/electronics2010041.
- Kristiansen, S.** (2005). *Maritime Transportation Safety Management and Risk Analysis*. Oxford: Elsevier Butterworth-Heinemann.
- Kristiansen, S.** (2013). *Maritime transportation: safety management and risk analysis*. Routledge, New York, United States. Langewiesche,
- Kunlun, S., Yan, L., & Ming, X.** (2011). A safety approach to predict human error in critical flight tasks. *Procedia Engineering*, 17, 52–62. doi:10.1016/j.proeng.2011.10.007.
- Kuzu, A. C., Akyuz, E., & Arslan, O.** (2019). Application of Fuzzy Fault Tree Analysis (FFTA) to maritime industry: A risk analysing of ship mooring operation. *Ocean Engineering*, 179: 128-134.
- Lavasani, S. M., Ramzali, N., Sabzalipour, F., & Akyuz, E.** (2015). Utilisation of Fuzzy Fault Tree Analysis (FFTA) for quantified risk analysis of leakage in abandoned oil and natural-gas wells. *Ocean Engineering*, 108, 729-737.
- Lee, S. J., Kim, J., & Jung, W.** (2013). Quantitative estimation of the human error probability during soft control operations. *Annals of Nuclear Energy*, 57, 318–326. doi:10.1016/j.anucene.2013.02.018.
- Lee, L.W. and Chen, S.M.** (2008). Fuzzy multiple attributes group decision-making based on the extension of TOPSIS method and interval type-2 fuzzy sets, in: *International Conference on Machine Learning and Cybernetics*, vol. 6, IEEE, 2008, 3260–3265.
- Lee, W. S., Grosh, D. L., Tillman, F. A., & Lie, C. H.** (1985). “Fault Tree Analysis, Methods, and Applications: A Review.” *IEEE Transactions on Reliability*, 3(3): 194–203. doi:10.1109/TR.1985.5222114.
- Li, S., Meng, Q., & Qu, X.** (2011). An Overview of Maritime Waterway Quantitative Risk Assessment Models. *Risk Analysis*, 32(3), 496–512. doi:10.1111/j.1539-6924.2011.01697.x.
- Marine Accident Investigation Branch** (2008). *Annual report 2008*. Southampton, UK: Marine Accident Investigation Branch.

- Martins, M.R., and Maturana, M.C.** (2010). Human error contribution in collision and grounding of oil tankers. *Risk Analysis*, 30, 674–698. doi:10.1111/j.1539-6924.2010.01392.x.
- Melin, P., and Castillo, O.** (2004). A New Method for Adaptive Control of Non-Linear Plants Using Type2 Fuzzy Logic and Neural Networks. *International Journal of General Systems*, 33, 289–304.
- Mendel, J. M.** (2007). Advances in type-2 fuzzy sets and systems. *Information Sciences*, 177(1), 84–110. doi:10.1016/j.ins.2006.05.003.
- Mendel, J. M., John, R., & Liu, F.** (2006). Interval Type-2 Fuzzy Logic Systems Made Simple. *Fuzzy Systems, IEEE Transactions On*, 14(6): 808–821. doi:10.1109/TFUZZ.2006.879986.
- Mentes, A., and Helvacioğlu, I. H.** (2011). An application of fuzzy fault tree analysis for spread mooring systems. *Ocean Engineering*, 38, 285–294. doi:10.1016/j.oceaneng.2010.11.003.
- Noroozi, A., Khan, F., Mackinnon, S., Amyotte, P., & Deacon, T.** (2014). Determination of human error probabilities in maintenance procedures of a pump. *Process Safety and Environmental Protection*, 92(2), 131–141. doi.org/10.1016/j.psep.2012.11.003.
- Noroozi, A., Khakzad, N., Khan, F., MacKinnon, S., & Abbassi, R.** (2013). The role of human error in risk analysis: Application to pre- and post-maintenance procedures of process facilities. *Reliability Engineering & System Safety*, 119, 251–258. doi:10.1016/j.ress.2013.06.038.
- Oriola, A.O., & Adekunle, A.K.** (2015). Assessment of Runway Accident Hazards in Nigeria Aviation Sector. *International Journal for Traffic and Transport Engineering*, 5(2), 82–92. doi:10.7708/ijtte.2015.5(2).01.
- Pan, H.S. and Yun, W.Y.** (1997). Fault tree analysis with fuzzy gates. *Computers and Industrial Engineering*, 33(3–4), 569–572.
- Pan, X. and Wu, Z.** (2018). Performance shaping factors in the human error probability modification of human reliability analysis, *International Journal of Occupational Safety and Ergonomics*, doi: 10.1080/10803548.2018.1498655.
- Park, K.S. and Lee, J.** (2008). A new method for estimating human error probabilities: AHP-SLIM. *Reliability Engineering & System Safety*, 93, 578–587. doi:10.1016/j.ress.2007.02.003.
- Parunov, J., Andric, J., Corak, M., & Kitarovic, S.** (2014). Structural reliability assessment of container ship at the time of accident. Proceedings of the Institution of Mechanical Engineers, Part M: *Journal of Engineering for the Maritime Environment*, 229(2), 111–123. doi:10.1177/1475090213506183.
- Pazouki, K., Forbes, N., Norman, R. A., & Woodward, M. D.** (2018). Investigation on the impact of human-automation interaction in maritime operations. *Ocean Engineering*, 153, 297–304. doi:10.1016/j.oceaneng.2018.01.103.
- Porter, J.** (2008). *Shipowners call for box weight checks at dock gate*. Lloyd's List, December 10 (59, 819): 1.

- Rashed, S. K.** (2016). The concept of human reliability assessment tool CREAM and its suitability for shipboard operations safety. *J. Shipp. Ocean Engineering*, 6, 348–355. doi:10.17265/2159-5879/2016.06.004.
- Rath, F.** (2008). Tools for Developing a Quality Management Program: Proactive Tools (Process Mapping, Value Stream Mapping, Fault Tree Analysis, and Failure Mode and Effects Analysis). *International Journal of Radiation Oncology Biology Physics*, 71(1SUPPL.), 187–190. doi:10.1016/j.ijrobp.2007.07.2385.
- Ren, D.** (2009). *Application of HFACS tool for analysis of investigation reports of accidents involving containerized dangerous goods*. (Master's Thesis) World Maritime University Dissertations. Retrieved from http://commons.wmu.se/all_dissertations/377.
- Rozuhan, H., Muhammad, M., & Niazi, U. M.** (2020). Probabilistic risk assessment of offshore installation hydrocarbon releases leading to fire and explosion, incorporating system and human reliability analysis. *Applied Ocean Research*, 101, 102282. doi:10.1016/j.apor.2020.102282
- Schiel, D., Ross, P., & Battershill, C.** (2016). Environmental effects of the MV Rena shipwreck: cross-disciplinary investigations of oil and debris impacts on a coastal ecosystem. *New Zealand Journal of Marine and Freshwater Research*, 50(1), 1–9. doi:10.1080/00288330.2015.1133665.
- Shafiee, M., Enjema, E., & Kolios, A.** (2019). An Integrated FTA-FMEA Model for Risk Analysis of Engineering Systems: A Case Study of Subsea Blowout Preventers. *Applied Sciences*, 9(6), 1192. doi:10.3390/app9061192.
- Shepherd, A.** (2001). *Hierarchical Task Analysis*. Taylor and Francis, London.
- Solmaz, M. S., Erdem, P., & Barış, G.** (2020). The Effects of Safety Culture on Occupational Accidents: An explanatory study in Container Terminals of Turkey. *International Journal of Environment and Geoinformatics*, 7(3), 356–364. doi:10.30897/ijegeo.749735.
- Solo, A. M. G.** (2015). Interval type-two fuzzy logic for quantitatively defining imprecise linguistic terms in politics and public policy. *Research Methods: Concepts, Methodologies, Tools, and Applications*, 2(4), 643–651. doi:10.4018/978-1-4666-7456-1.ch030.
- Spurgin, Anthony J.** (2010). *Human reliability assessment: theory and practice*. Taylor and Francis Group, LLC.
- Stanton, N. A.** (2006). Hierarchical task analysis: Developments, applications, and extensions. *Applied Ergonomics*, 37(1 SPEC. ISS.), 55–79. doi:10.1016/j.apergo.2005.06.003.
- Storhaug, G.** (2014). The measured contribution of whipping and springing on the fatigue and extreme loading of container vessels. *International Journal of Naval Architecture and Ocean Engineering*, 6(4), 1096–1110. doi: 10.2478/IJNAOE-2013-0233.
- Stuart, D.** (2007). *Misdeclared cargo led to Zim Haifa fire, court told*. Lloyd's List Intelligence, September 11.

- Swain, A.D.** (1987). *Accident Sequence Evaluation Program Human Reliability Analysis Procedure*. NUREG/CR-4772. US Nuclear Regulatory Commission.
- Swain, A.D. and Guttmann, H.E.** (1983). *Handbook of Human Reliability Analysis with Emphasis on Nuclear Power Plant Applications*. Nuclear Regulatory Commission, Washington, DC.
- Tu, J. and Lou, Y.** (2013). A SLIM Based Methodology for Human Reliability Analysis of Lifting Operations. *International Conference on Mechatronic Sciences, Electric Engineering and Computer (MEC)*. December 20-22, Shenyang, China.
- Uğurlu, Ö., Köse, E., Yıldırım, U., & Yüksekşildiz, E.** (2015). Marine accident analysis for collision and grounding in oil tanker using FTA method. *Maritime Policy and Management*, 42(2), 163–185. doi:10.1080/03088839.2013.856524.
- UNCTAD.** (2019). Review of Maritime Transport 2019. *United Nations Conference on Trade and Development*, New York, E.19.II.D.20, 31 January.
- Ung, S. T.** (2018). Human error assessment of oil tanker grounding. *Safety Science*, 104, 16–28. doi:10.1016/j.ssci.2017.12.035
- Ung, S. T.** (2019). Evaluation of human error contribution to oil tanker collision using fault tree analysis and modified fuzzy Bayesian Network based CREAM. *Ocean Engineering*, 179, 159–172. doi:10.1016/j.oceaneng.2019.03.031.
- URL-1** < <http://www.imo.org/>>, date retrieved 14.05.2020.
- URL-2** < <https://www.lloydslistintelligence.com/>>, date retrieved 04.12.2020.
- URL-3** < <https://www.iso.org/standard/20453.html>>, date retrieved 16.01.2021.
- URL-4** < <https://www.bic-code.org/size-and-type-code/>>, date retrieved 18.01.2021.
- Wang, L., Wang, J., Shi, M., Fu, S., & Zhu, M.** (2020). Critical risk factors in ship fire accidents. *Maritime Policy and Management*, 1–19. doi:10.1080/03088839.2020.1821110.
- Wang, W., Liu, X., & Qin, Y.** (2018). A modified HEART method with FANP for human error assessment in high-speed railway dispatching tasks. *International Journal of Industrial Ergonomics*, 67, 242–258. doi:10.1016/j.ergon.2018.06.002.
- Wang, L., Wang, Y., Cao, Q., Li, X., Li, J., & Wu, X.** (2014). A framework for human error risk analysis of coal mine emergency evacuation in China. *Journal of Loss Prevention in the Process Industries*, 30(1), 113–123. doi:10.1016/j.jlp.2014.05.007.
- Vesely, W.E** (2002). *Fault Tree Handbook with Aerospace Applications*. National Aeronautics and Space Administration, Version 1.1, (NASA).
- Vesely, W.E., Goldberg, F.F., Roberts, N.H., & Haasl, D.F.** (1981). *Fault Tree Handbook*. U.S Nuclear Regulatory Commission. NUREG–0492.

- Vestrucci, P.** (1988). The logistic model for assessing human error probabilities using the SLIM method. *Reliability Engineering and System Safety*, 21(3), 189–196. doi:10.1016/0951-8320(88)90120-2.
- Wiegmann, D. A. and Shappell, S. A.** (2017). *A human error approach to aviation accident analysis: The human factors analysis and classification system*. Routledge.
- Williams, J.C.** (1988). A data-based method for assessing and reducing human error to improve operational performance. In: *Proceedings of IEEE 4th Conference on Human Factor and Power Plants*. Monterey, California, pp. 436–453.
- Wong, T. J., and Yeh, C.W.** (2007). Validation of fault tree analysis in aviation safety management. *Journal of Air Transportation*, 12 (2), 43-57.
- Wróbel, K., Montewka, J., & Kujala, P.** (2017). Towards the assessment of potential impact of unmanned vessels on maritime transportation safety. *Reliability Engineering and System Safety*, 165, 155–169. doi: 10.1016/j.ress.2017.03.029.
- Wu, B., Yan, X., Wang, Y., Soares, C.G.** (2017). An Evidential Reasoning-Based CREAM to Human Reliability Analysis in Maritime Accident Process. *Risk Analysis*, 37, 1936–1957. doi:10.1111/risa.12757.
- Xi, Y. T., and Guo, C.** (2011). A method for marine human error probability estimate: APJE-SLIM. *Applied Mechanics and Materials*. 97–98. doi:10.4028/www.scientific.net/AMM.97-98.825.
- Xi, Y. T., Yang, Z. L., Fang, Q. G., Chen, W. J., & Wang, J.** (2017). A new hybrid approach to human error probability quantification–applications in maritime operations. *Ocean Engineering*, 138, 45–54. doi:10.1016/j.oceaneng.2017.04.018.
- Zadeh, L. A.** (1971). Similarity Relations and Fuzzy Ordering. *Journal of Information Sciences*, 3, 177– 206.
- Zadeh, L. A.** (1975). The Concept of a Linguistic Variable and Its Application to Approximate Reasoning–1, *Information Sciences*, 8, 199–249.
- Zhou, J. L., Lei, Y., & Chen, Y.** (2019). A hybrid HEART method to estimate human error probabilities in locomotive driving process. *Reliability Engineering and System Safety*, 188, 80–89. doi:10.1016/j.ress.2019.03.001.
- Zhou, Q., Wong, Y. D., Loh, H. S., & Yuen, K. F.** (2018). A fuzzy and Bayesian network CREAM model for human reliability analysis – The case of tanker shipping. *Safety Science*, 105, 149–157. doi.org/10.1016/j.ssci.2018.02.011.
- Zhou, Q., Wong, Y. D., Xu, H., Thai, V. Van, Loh, H. S., & Yuen, K. F.** (2017). An enhanced CREAM with stakeholder-graded protocols for tanker shipping safety application. *Safety Science*, 95, 140–147. doi:10.1016/j.ssci.2017.02.014.

APPENDICES

APPENDIX A: Figures





APPENDIX A

LISBOA PORT SUMMARY																								
DISCHARGED																	DENSITY		1025					
PORT	FULL			EMPTY			TOTAL					REEFER			IMDG			ACTUAL DRAFTS						
	20	40	TTL	20	40	TTL	20	40	TEU	TTL	WEIGHT	20	40	TTL	20	40	TTL	FORE	8,35		Commence of Operation			
Lisboa	10		10	75	34	109	85	34		119	578							MEAN	9,00		02.05.2020 08:15:00			
LOADED																	AFT		9,72		Operation Completed			
PORT	FULL			EMPTY			TOTAL					REEFER			IMDG			TRIM	1,37		03.05.2020 11:20:00			
	20	40	TTL	20	40	TTL	20	40	TEU	TTL	WEIGHT	20	40	TTL	20	40	TTL	LOAD MASTER						
Praia	38	18	56				38	18	74	56	1363	1	8	9	1	2	3	FORE	8,02		BM		86,0	
Mindelo	14	3	17				14	3	20	17	372	1		1	1		1	MEAN	8,82		GM		0,64	
Bissau	26	14	40				26	14	54	40	953		6	6	1	3	4	AFT	9,63		BW /TANK		1164/10	
																		TRIM	1,61		FW		94	
TTL	78	35	113				78	35	148	113	2688	2	14	16	3	5	8	SF	75,0		DISP.		29289	
TRANSIT																								
	20	40	TTL	20	40	TTL	20	40	TEU	TTL	WEIGHT	20	40	TTL	20	40	TTL	REEFERS		IMDG CONTAINERS				
Praia	42	21	63				42	21	84	63	1347		4	4	4	1	5	20"	2		CLASS	ITEM	MTS	
Mindelo	14	12	26				14	12	38	26	482		3	3		1	1	40"	33		2,2	2		
Bissau	492	78	570				492	78	648	570	14765		12	12	13		13	OOG		3		9		
																		20"	4		5,1	3		
TTL	548	111	659				548	111	770	659	16594		19	19	17	2	19	RESTOW FULL		6,1		1		
DEPARTURE																	20"	2		8		8		
	20	40	TTL	20	40	TTL	20	40	TEU	TTL	WEIGHT	20	40	TTL	20	40	TTL	40"			9		4	
Praia	80	39	119				80	39	158	119	2710	1	12	13	5	3	8			TTL		27	282,00	
Mindelo	28	15	43				28	15	58	43	854	1	3	4	1	1	2							
Bissau	518	92	610				518	92	702	610	15718		18	18	14	3	17							
TTL	626	146	772				626	146	918	772	19282	2	33	35	20	7	27							

Figure A.1 : Port Lisbon cargo operation details.

Human error is one of the significant contributing factors in increasing marine accidents. The consequences of marine accidents pose potential harm to the marine environment and human life. This study is designed to assess human (Seaman) error potentials contribution to maritime environmental risk management.

Your answers will be kept strictly confidential and will not be shared with third parties in any way!!!

Your candid answers to the survey will allow research to draw correct conclusions and inferences and to provide utmost contribution to estimate human errors and data about the safety performance of seafarers during the loading operation.

MARINE EXPERTS' PROFILE DETAILS

Name & Surname :
Company & Position :
Age :
Gender :
Educational Level :
Containership Experience :

LINGUISTIC TERMS

VERY LOW	LOW	MEDIUM LOW	MEDIUM	MEDIUM HIGH	HIGH	VERY HIGH
VL	L	ML	M	MH	H	VH

The linguistic terms are assigned for each sub-tasks given below to determine **how these factors impact human errors** throughout the containership loading operation.

'Please select the proper one above for determined sub-task below and **fill the box with number such as 1,5,7..etc.**'

CONTAINERSHIP LOADING OPERATION PROCESSES

Sub-Tasks	Task Description	Performans Shaping Factors						
		Stress	Experience	Training	Fatigue	Time Lin.	Complexity	Safety C.
		MH	H	ML	H	VH	M	H
	1. PRE-ARRIVAL	(Ext. Low)9 ↔ 1 (Ext. High)						
1.1	Prepare stowage and bay plan	7	3	6	3	4	5	2
1.2	Consider Max. Tier stack weight value as well as max stack weight while preparing stowage plan							
1.3	Check the provisional list of dangerous goods							
1.4	Check if the stowage plan is in accordance with the requirements of the IMDG Code							
1.5	Check if the stowage plan is proper to follow the reefer container process flowchart							

Figure A.2 : The designed survey utilised for HEP assessments.

	2. BEFORE LOADING	(Ext. Low)9 ↔ 1 (Ext. High)						
2.1	Check if the accommodation ladder is free from the crane path at the pier							
2.2	Make sure that the auto-heeling pump is actively running before cargo operation							
2.3	Make sure that all lashing equipment (twist lock, cone, bar) are qualified and ready for use							
2.4	Check if any equipment is on the hatch cover before the operation							
2.5	Be ensure if the hatch covers are not damaged on the shoreside							
2.6	Check if any equipment is in the hold bottom							
	3. DURING LOADING							
	Human Safety							
3.1.1	Make sure that all crew on deck use PPE							
3.1.2	Use a safety belt when working/climbing on containers							
3.1.3	Keep clear from the container passage area							
3.1.4	Be aware of the risks of mislaid equipment on the operated container							
3.1.5	Be aware of the risks of lashing operations on bays at which cargo operations continue							
	Ship/Cargo Security							
3.2.1	Check if any oil is dropped off from the gantry to the deck							
3.2.2	Check all cell guides against any damage during operation							
3.2.3	Check the seal of loading containers							
3.2.4	Check if the top cover of the OT container is damaged and not prevent another container which put on them.							
3.2.5	Check the IMO signs/labels of dangerous cargoes							
3.2.6	Check the tightness of all straps on flat rack containers if any							
3.2.7	Make sure that the on/off switch is kept off before connecting of reefer plug							
3.2.8	Check the temperature setting degree and ventilation and humidity settings (%) of the reefer container							
3.2.9	Consider the height while loading HC/OT containers in the hold							
3.2.10	Inform C/O in case the flatrack container is overhighed or overgauged than declared							
3.2.11	Check if loading containers in balance on to port/starboard side of the ship							
3.2.12	Inform the office-charterer-agent if the ship heels more than 5 degrees during loading							

Figure A.2 (continued) : The designed survey utilised for HEP assessments.

	3. DURING LOADING	(Ext. Low)9 ↔ 1 (Ext. High)					
3.2.13	Inform C/O if hook spreaders are used for cargo operations						
3.2.14	Check if the leakage containers on board						
3.2.15	Inform C/O in case damaged container is observed						
3.2.16	Prepare interchange report for damaged containers						
3.2.17	Inform the charterer and management office if the container is heavily damaged						
3.2.18	Check the ship's ropes during the operation frequently						
3.2.19	Keep the drafts under strict control during cargo operation						
	4. AFTER LOADING						
4.1	Check if the visibility line and/or steering light is blocked						
4.2	Confirm that all containers are loaded in accordance with planned stow.						
4.3	Check the final setpoint value of reefer containers and kept the records in file						
4.4	Make sure that there are no lashing gears randomly thrown on deck						
4.5	Inspect that all lashing equipment are exact/not missing						
4.6	Check and confirm the position of the gearboxes visually						
4.7	Make sure that all twist locks are in the locked position						
4.8	Check if the cleats on all sides of all hatch covers are locked						
4.9	Check if the lashing operation is carried out in compliance with Cargo Securing Manuel						
	5. PRE-DEPARTURE						
5.1	Record the final drafts on port log book						
5.2	Make sure that auto-heeling pump is properly deactivated						
5.3	Make sure that the GM value complies with the limit of the minimum required GM value that given by loadmaster +40 cm limit						
5.4	Check if sea condition %95 stress is exceeded						
5.5	Make sure that stress values are calculated and signed						
5.6	Ensure that final lists/documentation and certificates of goods actually loaded are provided						
5.7	Check if the ship and shore cranes are clear						
5.8	Check the ship's and gantry's air drafts						
<i>THANKS FOR YOUR SUPPORT...</i>							

Figure A.2 (continued) : The designed survey utilised for HEP assessments.

The consequences of marine accidents pose potential harm to the marine environment and human life. Human error is one of the significant contributing factors in increasing marine accidents. This study is designed to evaluate the criticality of the operational activities as well as human error potential contributions to maritime transportation risk management.

Your answers will be kept strictly confidential and will not be shared with third parties in any way!!!

Your candid answers to the survey will allow research to draw correct conclusions and inferences to perform risk assessments and data about the human-related errors during the loading operation at the container terminal.

MARINE EXPERTS' PROFILE DETAILS

Name & Surname :
 Company & Position :
 Age :
 Gender :
 Educational Level :
 Containership Experience :

LINEAR SCALE VALUE '9 ↔ 1'								
EXTREME LOW	VERY LOW	LOW	MEDIUM LOW	MEDIUM	MEDIUM HIGH	HIGH	VERY HIGH	EXTREME HIGH
9	8	7	6	5	4	3	2	1

** A value from 'extreme low' to 'extreme high' in a liner scale shall be nominated by marine experts.*

If related Performance Shaping Factor (PSF) has a significant impact upon the occurrence of Basic Event (BE) value '1=Extreme High' is assigned.

*'Please select the proper one above for determined basic events below and **fill the box with number such as 1,5,7..etc.**'*

CONTAINERSHIP LOADING OPERATION PROCESSES								
Basic Event	Top Event (TE) Container Loss	Performans Shaping Factors						
		Stress	Experience	Training	Fatigue	Time Lim.	Complexity	Safety C.
BE1	Incorrect weight distribution	(Ext. Low)9 ↔ 1 (Ext. High)						
BE2	Mobility due to poor stack	7	3	6	3	4	5	2
BE3	Inaccurate packing							
BE4	Misdeclaration/undeclaration of the actual type/materials of cargo							
BE5	Misdeclaration/undeclaration of the actual weight of the container							
BE6	Loose lashing gear (lashing bars and turnbuckles)							
BE7	Unlocked hatch cleats							

Figure A.3 : The designed survey utilised for risk analysis.

		Performans Shaping Factors						
Basic Event	Top Event (TE) Container Loss	Stress	Experience	Training	Fatigue	Time Lim.	Complexity	Safety C.
		<i>(Ext. Low)9 ↔ 1 (Ext. High)</i>						
BE8	Unlocked twist locks							
BE9	Exceeding the recommended lashing forces							
BE10	Deck fittings failure							
BE11	Broken/bent equipment (twist locks, turnbuckles, bars, etc.)							
BE12	Improper equipment for fixed deck fittings							
BE13	Gantry/Mobile crane failure							
BE14	Operator handling failure							
BE15	Port restrictions							
BE16	Lack of awareness for wind effect							
BE17	Inadequate planning							
BE18	Miscommunication as to the operation's actual process							
BE19	Lack of communication between crew and stevedore/foreman							
BE20	Hook Spreader Usage							
BE21	Leakage container loading							
BE22	Incorrect special-type container loading							
BE23	Missing equipment							
BE24	Ballast change failure							
BE25	Heeling/ballast system failure							
BE26	Exceeding the max. number of containers in each stack							
BE27	Exceeding permissible stack weight							
BE28	Extreme partial loading							
BE29	Exceeding the max GM and stress values							
BE30	Neglecting permissible sequences of masses in stacks							

Figure A.3 (continued) : The designed survey utilised for risk analysis.

CURRICULUM VITAE

Name Surname : Pelin ERDEM

EDUCATION:

- **B.Sc.** : 2010, Karadeniz Technical University, Sürmene Faculty of Marine Science, Maritime Transportation and Management Engineering Department
- **M.Sc.** : 2016, Dokuz Eylül University, Maritime Faculty, Department of Marine Transportation Engineering, Maritime Security, Safety and Environmental Management Programme

PROFESSIONAL EXPERIENCE AND REWARDS:

- Research Assistant
- Oceangoing Chief Officer

PUBLICATIONS, PRESENTATIONS AND PATENTS ON THE THESIS:

- **Erdem, P.**, Akyuz, E., & Arslan, O. (2021). The Role Of Human Factors In Maritime Environmental Risk Assessment: A Case Study Of Oil Spill Response, *International Journal of Maritime Engineering*, 163(2). doi:10.5750/ijme.v163iA2.761.
- **Erdem, P.**, and Akyuz, E. (2021). An Interval Type-2 Fuzzy SLIM Approach To Predict Human Error In Maritime Transportation. *Ocean Engineering*, 232, 109161. doi:10.1016/j.oceaneng.2021.109161.

OTHER PUBLICATIONS, PRESENTATIONS AND PATENTS:

- Solmaz, M. S., **Erdem, P.**, & Barış, G. (2020). The Effects of Safety Culture On Occupational Accidents: An explanatory Study In Container Terminals of Turkey. *International Journal of Environment and Geoinformatics*, 7(3), 356–364. doi:10.30897/ijegeo.749735.
- **Erdem, P.**, and Tavacıoğlu, L. (2019). A Comprehensive Study On Assessment of Safety Climate Based On Theory of Planned Behaviour in Maritime Domain. *III. Global Conference on Innovation in Marine Technology and the Future of Maritime Transportation*, GMC '19 , April 2019, İzmir, Turkey.

